



The Clean Air Act Amendments: Spurring Innovation and Growth While Cleaning the Air

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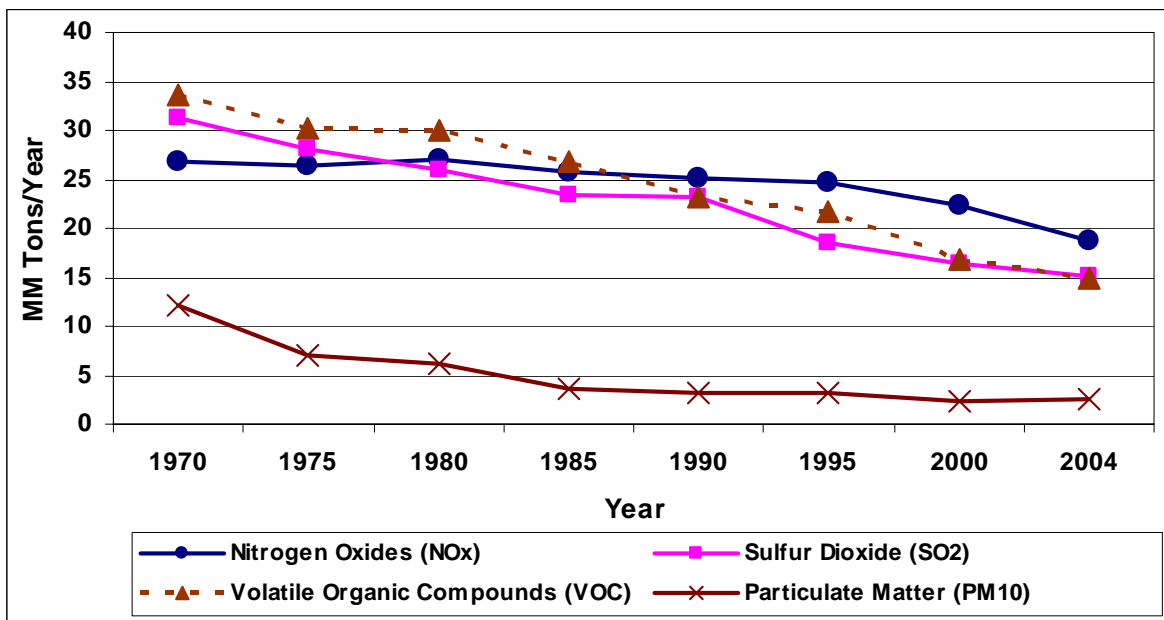
I. Introduction

The United States experience with air pollution control has been one of impressive successes. As the 15th anniversary of the historic Clean Air Act Amendments of 1990 (CAAA) approaches, it is worth stepping back to review the history of the legislation and the reactions of the affected industries. Although the CAAA led to tight standards, they left the affected industries with wide latitude in ways to meet those standards. This flexibility encouraged the maximum creativity and innovation among these industries. Faced with the challenge of meeting increasingly stringent standards, affected entities responded with innovations that met or even exceeded the requirements. As a result, the innovations spurred by the CAAA not only led to reduced emissions at lower costs, but also helped build a stronger economy through growth in pollution control industries.

This paper analyzes the history of the CAAA with emphasis on areas with significant innovations and technological development, which helped clean the air and were instrumental in the growth of pollution control industries, both domestically and internationally.

Although air pollution has not been eliminated, significant progress has been made in improving the quality of the air in most U.S. cities and communities. Since Congress enacted the Clean Air Act in 1970, total national emissions of the six criteria air pollutants have decreased more than 25 percent.¹ Figure 1 shows these declining trends for four criteria pollutants -- sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM), and volatile organic compounds (VOC) -- that are the focus of this paper.

Figure 1: Total Emission Trends



Source: *Air Emission Trends*, EPA.

Notably, these improvements accompanied significant growth in the nation's population and economic activity. Gross Domestic Product (GDP), the most common measure of economic activity, increased by more than 160 percent in this time period, and the population increased

¹ "Draft Report on the Environment", U.S. Environmental Protection Agency, 2003.

from 203 million to nearly 300 million during the same period. Moreover, energy consumption increased by more than 42 percent, and vehicle miles traveled increased by more than 149 percent.² Also, as will be shown in this paper, success in reducing emissions was achieved in conjunction with substantial growth in pollution control industries. Seen in this context, the progress made to date is not only impressive, but gives confidence that the nation's ultimate air quality goals will be achieved without sacrificing prosperity.

Summary of Findings

The remainder of this report is divided into seven sections, including four that are devoted to innovations in distinct categories of pollution sources. These are followed by sections noting some common sources of innovations in all of the categories, a discussion of the positive effects of pollution control on employment and the economy, and a summary of lessons learned.

Section II argues that the CAAA stimulated investment in technology to achieve the needed emissions reductions for large, stationary sources of air pollution. Innovation was applied to technologies serving a broad spectrum of pollutants and pollutant sources. Flexibilities in approach, such as those used for the allowance trading program for acid gases, led the way for more efficient controls at lower costs and encouraged similar programs in the U.S. and overseas. The section also shows how flue gas desulfurization (FGD) technologies evolved due to the CAAA, gaining improvements in reliability at lower costs. Innovations in SCR and ultra-low NOx burner technologies not only led to their accelerated penetration for NOx control, but also to healthy competition between manufacturers to secure their share of the market. Initial improvements in mercury control technologies for waste incinerators now are leading the way for innovations in sorbent technologies and other multipollutant controls for power plants, and are helping U.S. companies become a world leader in these technologies. Technological innovations for industrial paints, coatings, and adhesives have led to significant reductions in VOC emissions.

Section III argues that innovations for on-road mobile source technologies were driven in part by improvements experienced in California and technological changes in developing low-sulfur fuel. Mobile source innovations included better fuel control, faster catalyst light-off, improved catalyst formulations, increased evaporative emissions control, and a tighter PM standard for light-duty diesel vehicles. Moreover, standards under the CAAA now are leading the way for alternative fuel vehicles such as hybrid electric and fuel cell vehicles. The section concludes with a discussion of the more promising mobile source technologies expected to further reduce emissions from gas and diesel light-duty vehicles in the 2007 to 2010 timeframe.

Section IV claims that emissions reductions for off-road and nonroad sources were accomplished because technological advancements in diesel engines for highways could be applied to nonroad engines. The section contends that several rules under the CAAA, including the Large Industrial Spark Ignited (SI) and the Small SI engine rules, were responsible for improved fuel control, on-board diagnostics, catalysts, and engine cooling and oil controls, expected to bring significant reductions in hydrocarbon, NOx, and CO emissions by 2020.

Section V discusses the history of innovations in petroleum refining and clean fuels technologies. The CAAA spurred two important process changes – diesel desulfurization and fluid catalyst cracking technologies – that set the stage for significant reductions in the sulfur

² *Ibid.*

content of fuel, which will be required in the near future. This section also presents a discussion of alternative fuels, such as methanol, ethanol, propane, natural gas, and hydrogen, and highlights the recent trends in use of alternative fuel vehicles.

Section VI argues that much of the history of technological changes specific to the different sources was influenced by innovations in fields such as information technology and material science. Improvements in computational fluid dynamic software and the availability of low-cost computers facilitated more rapid and less expensive development of designs for air pollution control systems with improved performance and reliability. Moreover, advanced controls and instrumentation technologies led to more efficient use of low-NO_x burners and FGDs. The section concludes with two examples of advances in material science where the incentives provided by the proper regulatory regime enabled U.S. firms to take a leadership role.

Section VII discusses the growth of the U.S. environmental technology industries. Total revenue grew from approximately \$30 billion in 1972 to \$115 billion in 1990 and \$215 billion in 2002. These industries not only provided direct employment in manufacturing pollution control equipment, but also created indirect employment in supporting industries and the service sectors, such as wholesale and retail trades. Total number of jobs, including both direct and indirect employment, grew from approximately 1.3 million in 1977 to 3.2 million in 2002. Moreover, this growth was not confined to the domestic markets. U.S. exports of environmental technologies totaled about \$30 billion in 2004, with a phenomenal 130 percent export growth between 1993 and 2003. Much of that growth was driven by the demand from the emerging Asian markets for innovative pollution control technologies.

Section VIII concludes with lessons learned from the past 15 years to better inform the debate as the nation looks ahead to meeting future air quality goals. The CAAA achieved greater levels of control and lower costs than ever envisioned. It succeeded because it:

- Focused on results and allowed flexibility in achieving them;
- Forced innovation by setting ambitious emissions limits;
- Employed flexible and even innovative approaches to regulation;
- Set goals for the long term, not limited by what was technologically achievable in the near term; and
- Fostered an American industry with growth in both the domestic and export markets.

II. Innovations and Technological Developments for Stationary Sources

The CAAA spurred innovations and technological developments in pollution control for many types of sources of pollution. The following sections discuss the evolution of the rules in response to the requirements of the CAAA and its various Titles (and the original Clean Air Act of 1970, where applicable). The discussion is organized by categories of pollution sources and summarizes the innovations that have already taken place or are expected to occur in the near future as the regulated communities strive to meet federally mandated requirements.

Stationary Source Controls

It is widely recognized that the primary reason that owners of large, stationary sources of air pollution install pollution control technology is in response to regulatory requirements to reduce pollution. By mandating reductions in air pollution emissions -- rather than specific technical remedies -- the CAAA stimulated investment in technology to achieve the needed emissions reductions. Thus innovation was applied to technologies serving a broad spectrum of pollutants and pollutant sources.

Summary of Stationary Source Regulations

The Clean Air Act of 1970 was the first comprehensive attempt at the federal level to regulate what are known as the “criteria air pollutants.” Congress made substantive revisions to the Act in 1990 to alleviate problems of acid rain, regional smog, and air toxics in U.S. cities and communities. Several components of the 1990 Amendments were relevant for the stationary source emissions, and the relevant Titles and their impacts are discussed below.

Title I of the CAAA established requirements for localities to meet standards for air quality designed to protect public health. These standards were known as National Ambient Air Quality Standards (NAAQS). Title I did not prescribe how the localities would meet the NAAQS. Instead, it set deadlines for meeting the NAAQS and identified penalties for missing those deadlines. The states were responsible and are held accountable for meeting the standard. At the time of the CAAA of 1990, the U.S. Environmental Protection Agency (EPA) was able to identify parts of the country that were in violation of the NAAQS. Also, there was some understanding of the chemical reactions in the atmosphere that contributed to these pollutants and the transport of pollutants between regions. Throughout the Ozone Transport Region (OTR), a region identified in the CAAA that extends from northern Virginia to Maine, it was necessary in 1995 to use Reasonably Available Control Technology (RACT) on major combustion sources, such as power plants and industrial boilers, to control NO_x on major sources.

Because of the significance of NO_x in ozone formation, EPA issued the NO_x SIP Call in 1998 under the authority of the CAAA.³ The NO_x SIP Call expanded the region of the country where ground-level ozone transport was known to be a problem from the OTR to a larger region encompassing much of the Northeast, Midwest, and parts of the Southeast. The SIP Call established a program to cap NO_x emissions in this region. The understanding of the causes of fine particulate and the health effects of fine PM also improved during the period since passage of the CAAA. EPA recognized the increased need to control both NO_x and SO₂ emissions to

³ State Implementation Plans, or SIPs, are used when federal authorities set ambient standards and the states are responsible for carrying out the regulations. States are allowed to have stronger pollution controls than what the federal government mandates.

reduce fine PM. Under the authority of the CAAA, the Clean Air Interstate Rule (CAIR) was established in 2005 to satisfy requirements of Title I. CAIR expands the regions for NO_x and SO₂ controls, and, recognizing that fine PM is an annual problem, also makes annual controls of NO_x mandatory throughout much of the affected region.

Title III, the provision of the CAAA that addresses toxic pollutants, stimulated the need to control toxic emissions from various sources, such as mercury and hydrochloric acid (HCl) from waste incinerators, and toxic pollutants from a wide range of manufacturing facilities. In response to Title III, all large waste incinerators in the U.S. were retrofitted with acid gas control technology (mostly dry scrubbing) and mercury and dioxin control technology (primarily activated carbon injection). The development and use of activated carbon to control mercury from incinerators laid the groundwork for mercury controls for utility boilers as well. Manufacturing facilities, where process modification or material substitution was not possible to reduce emissions of toxic pollutants, installed control technology, including thermal and catalytic oxidizers, to control organic emissions.

Title IV of the CAAA addressed emissions of acid gases -- particularly SO₂ and NO_x -- from utility and other large sources. This provision of the CAAA relied on a groundbreaking allowance trading system that provided the framework for allowance trading in several other air regulatory programs in the U.S. and overseas. This provision of the CAAA required utility power plants and other large acid gas emitters to control and monitor those emissions. In response to Title IV, power plants switched to lower sulfur fuels and installed FGD systems, low NO_x combustion hardware, post combustion de-NO_x systems, and Continuous Emission Monitoring Systems (CEMS).

Innovations in Stationary Source Technologies

The Clean Air Act of 1970 was not only successful in cleaning the air but also exceeded expectations with respect to the level of innovations and learning-by-doing within the pollution control industry. Below is an overview of technological changes for various control technologies.

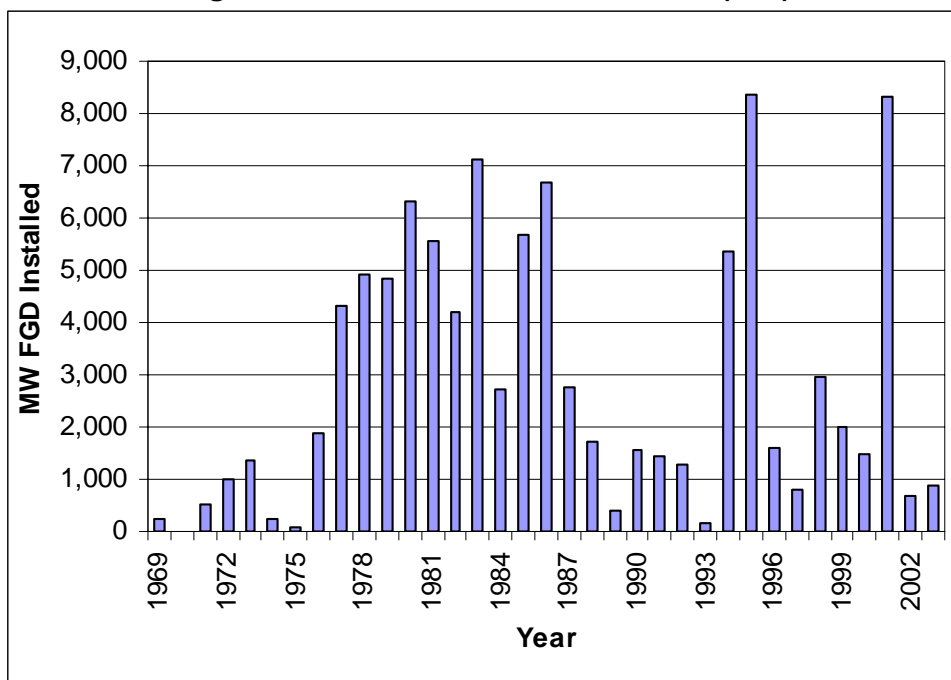
Evolution of SO₂ Control Technologies

One area where the CAAA was very effective in spurring innovation is the control on SO₂ emissions in response to Titles I and IV. In addition to switching to low sulfur coal for fuel, power plants used FGD (or scrubbers), to remove sulfur resulting from the burning of coal. FGDs have gone through significant improvements in the last two decades.

The original Clean Air Act of 1970 imposed the need to control SO₂ emissions from utility boilers. As a result of the New Source Performance Standards (NSPS) for pollutant emissions encompassed in that legislation, new utility power plants that utilized high sulfur coal needed to install scrubbers. In the early days of the Clean Air Act (in the late 1970s and early 1980s), scrubbers achieved less than 90 percent removal efficiencies. However, with continued use and learning-by-doing, scrubbers today consistently achieve over 95 percent removal efficiencies, with some high velocity limestone forced oxidation (LSFO) systems achieving over 99.6 percent efficiency. These improvements were driven by the SO₂ regulations under Title IV and the consequent understanding of scrubber chemistry, improvements in absorber design, and technology maturation.

A movement to install FGDs occurred in response to the 1970 Clean Air Act. In addition, Title IV of the CAAA increased the need to control SO₂ emissions from utility boilers. The innovative emissions trading program created by Title IV caused power plant owners to explore the most cost-effective means of reducing SO₂ emissions at their facilities. According to Energy Information Administration (EIA) data, about 63,000 megawatts (MW) of FGDs had been installed in the U.S. by 1990. Figure 2 shows FGD installations from 1969 through 2003.

Figure 2: FGD Installations 1969-2003 (MW)



Source: Energy Information Administration.

By far, the most widely used approach to reduce SO₂ emissions in response to Title IV has been switching to lower sulfur coal, much of it subbituminous coal mined in the Powder River Basin (PRB). By 1995, about 47,000 MW of Title IV-affected units switched fuels or blended lower sulfur fuels to comply with this requirement (see Table 1). Each coal-fired boiler is designed with a particular fuel in mind. Therefore, there were many challenges in switching from an eastern bituminous coal to PRB coal. First, PRB coal has a lower heating value than eastern bituminous coal, resulting in the need to feed more fuel to the boiler to achieve the same heat input. Second, PRB fuels tend to have more challenging slagging characteristics, which are exacerbated by the low heating value and the need to feed more coal. Finally, electrostatic precipitators (ESPs), the most common PM control devices, do not work as well with low sulfur coals as they do with higher sulfur coals. Hence, switching fuels was not straightforward and could result in serious operating problems. To address these challenges, industry developed improved furnace combustion and cleanliness control systems. Special furnace cleaning systems and furnace sensors permitted the use of the new fuels, while improving overall boiler efficiency and reliability. The facilities also developed methods, such as flue gas conditioning, to improve ESP performance at low cost. One benefit of the switch to PRB fuel was the lower NO_x emissions rate that is produced by the low-nitrogen, high-volatile PRB fuel.

Table 1: Profile of Compliance Methods for Title IV Units

Compliance Method	Number of Generators	Average Age (years)	Affected Nameplate Capacity (megawatts)	Allowances (per year)	1985 SO ₂ Emissions (tons)	1995 Emissions (tons)	Percentage of Total Nameplate Capacity Affected by Phase I	Percentage of SO ₂ Emission Reductions in 1995
Fuel Switching and/or Blending	136	32	47,280	2,892,422	4,768,480	1,923,691	53	59
Obtaining Additional Allowances	83	35	24,395	1,567,747	2,640,565	2,223,879	27	9
Installing Flue Gas Desulfurization Equipment (Scrubbers)	27	28	14,101	923,467	1,637,783	278,284	16	28
Retired Facilities	7	32	1,342	56,781	121,040	0	2	2
Other	8	33	1,871	110,404	134,117	18,578	2	2
Total	261	32	88,989	5,550,821	9,301,985	4,444,432	100	100

Source: Energy Information Administration, "The Effects of Title IV of the Clean Air Act Amendments of 1990 on Electric Utilities: An Update," DOE/EIA-0582(97), Distribution Category UC-950, March 1999. Refer to Table 2, page 6, for more information on the sources of the data and relevant information.

Although fuel switching was the most common way for power plants to reduce their SO₂ emissions in the 1990s, FGD systems were installed by a number of power plants in response to the CAAA. According to EIA, by the end of 1999, the total capacity of FGDs in the U.S. was up to 88,000 MW, an increase in installed FGD systems of about 25,000 MW over the decade. The choice between fuel switching and scrubbing was driven by economics. Those plants that chose to switch fuel generally had access to lower cost low sulfur fuel than those that chose to use scrubbers. Therefore, the plants that switched fuel either had good rail access to low sulfur western fuels or barge access to low sulfur South American fuels.

With Phase II of Title IV in place, banked SO₂ allowances have been consumed at a rapid rate, increasing SO₂ allowance prices from under \$200 per ton to more than \$800 per ton in the last two years.⁴ With increased SO₂ allowance prices, utilities are now turning to FGDs for SO₂ control and compliance with Title IV. The motivation to keep total FGD capital and operating costs low has stimulated a drive toward reducing capital cost, improving reliability, and enhancing reduction efficiency. These three goals have been achieved in a variety of ways. Reduction in capital cost has been accomplished through the use of standardized, modular designs and through redesign of the systems to reduce the number of components. For example, the Tampa Electric Big Bend FGD system uses one absorber to treat the flue gas from two roughly 450 MW units — for a total of about 900 MW. The FGD system installed to treat the gas from Big Bend Units 1 and 2 was at a cost of about \$100 per kilowatt (kW).⁵ The recently completed Centralia FGD project uses one absorber for each of the 700 MW units. The Centralia FGD system total project cost was about \$103 per kW.⁶ These recent costs are roughly half of the \$200 per kW capital cost previously thought to be the norm for wet FGDs.

The drive to improve reliability stimulated the increased use of forced oxidation over natural oxidation wet FGD — to improve gypsum conversion and reduce scaling in the vessel. Improved

⁴ Allowances provide authorization to the affected units to emit a fixed amount of the pollutant. Banking of allowances refers to an option in which affected units can save the allowances not needed to meet current emission requirements in order to use them to meet emission needs at a future date.

⁵ "Tampa Electric announces plans to reduce emissions from Big Bend Units One and Two," Tampa Electric News Release, July 20, 1998, available at: <http://www.tampaelectric.com/TENWNewsRelease.cfm?article=110>.

⁶ Miller, M., Webster, L., Rader, P., Bussell, C., "Centralia WFGD System: State-of-the-Art SO₂ Compliance," Combined Power Plant Air Pollution Control Mega Symposium, paper #40, May 19–22, 2003, Washington, DC.

reliability also was achieved through the use of materials that are less susceptible to the corrosive effects of the flue gases: fiberglass reinforced plastic (FRP), corrosion-resistant alloys, and plastic-lined vessels, which were not employed to a great degree in earlier FGD systems. Along with others, these technology developments have led to improved performance. Wet FGD technology currently is capable of more than 98 percent removal of SO₂, and dry FGD is capable of well over 90 percent removal in most cases. These performance improvements contribute to lower cost of removal per ton, which is an important measure of cost when emissions allowances are traded.

Evolution of NO_x Control Technologies

Selective Catalytic Reduction Technology

Titles I and IV of the CAAA created a need to reduce NO_x emissions. Selective Catalytic Reduction (SCR) had been employed in both Europe and Japan to reduce NO_x emissions prior to use in the U.S. Although SCR use in these countries generally was viewed as successful, it was not clear whether the experience could be applied directly to U.S. facilities, for the following reasons:

- SCR catalyst was susceptible to chemical and physical damage from impurities in the flue gas. Because U.S. coals are different from overseas coals, concerns arose that unfamiliar impurities in the U.S. coals would cause unacceptable levels of damage;
- High sulfur U.S. coals were expected to present a particularly difficult challenge due to concerns about sulfur trioxide (SO₃) formation; and
- U.S. regulations differed from overseas regulations and tended to favor SCRs with higher reductions and lower baseline emissions rates than experienced in Europe or Japan.

Collaboration between government and industry was necessary to address these concerns. Several development and test programs successfully showed that the challenges associated with implementation of SCR on U.S. coals at high (about 90 percent) removal rates could be successfully addressed. These NO_x removal rates were well above the rates that were typical at European or Japanese installations. Catalyst formulations that are resistant to (but not immune from) catalyst impurities present in U.S. coals were developed and proved to provide longer catalyst lifetimes than nonarsenic-resistant catalysts. SO₂ conversion to SO₃ was shown to be controlled to levels that are manageable, particularly with the use of low SO₃ conversion catalyst formulations. Catalysts with thin walls (for high open areas) and good resistance to erosion were developed. High NO_x removal rates in the range of 90 percent were shown to be achievable while maintaining reliable facility operation.

Figure 3 shows the annual MWs of coal-fired SCR systems that were brought online through 2004 or are projected to be brought online from 2005–2008. The commissioning of nearly all of these SCRs occurred over a span of less than five years. Yet, despite the rapid deployment, SCR has been shown to be reliable at providing the necessary NO_x removal rates.

Figure 3: U.S. Coal-Fired SCR Capacity

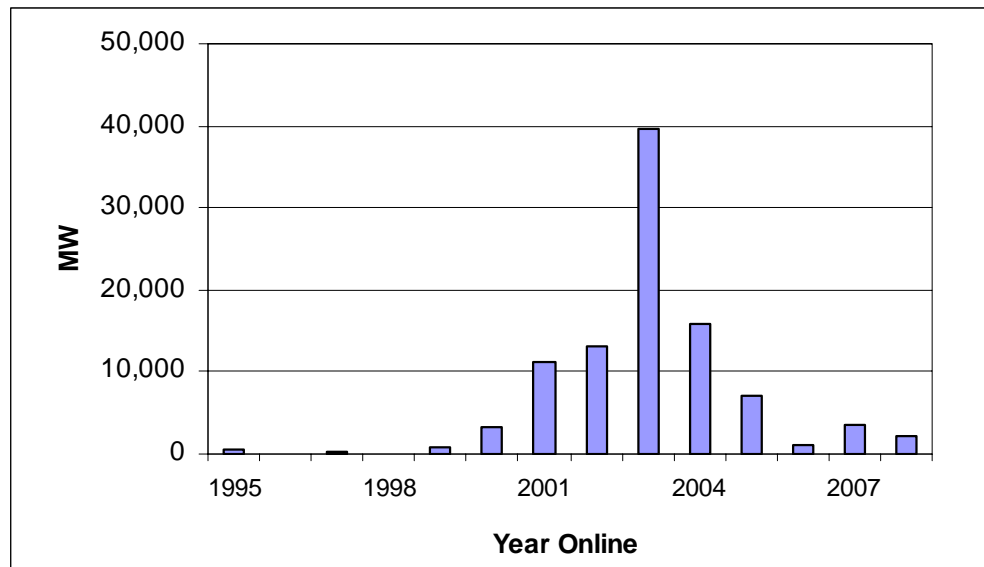
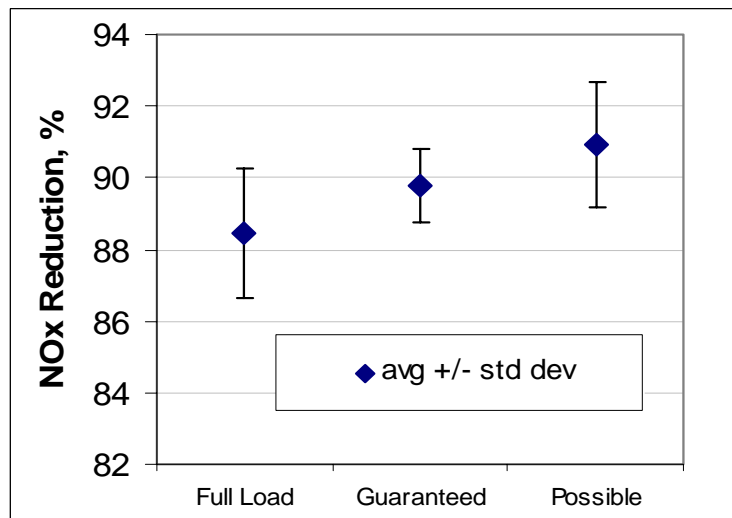


Figure 4, which is based on a survey of SCR operators, shows SCRs installed in response to the SIP Call are regularly operated at close to 90 percent removal at full load. All met their guarantees of about 90 percent removal, and all could be reliably operated at higher NO_x reduction levels if desired.⁷ Moreover, all of the operators who participated in the survey mentioned that the SCRs installed in response to the SIP Call met or exceeded their expectations for overall reliability. This very rapid deployment of SCR at performance levels not previously shown and the high degree of reliability demonstrates that this technology has advanced substantially in response to the requirements of the CAAA.

Figure 4: Percent NO_x Reduction of SIP Call SCRs



⁷Staudt, J., Khan, S., Oliva, M., "Reliability of Selective Catalytic Reduction (SCR) and Flue Gas Desulfurization (FGD) Systems for High Pollutant Removal Efficiencies on Coal Fired Utility Boilers," The 2004 Combined Utility Air Pollution Control Conference, The Mega Symposium, August 30-September 2, 2004, Washington DC.

Ultra-Low NOx Burners

Reducing NOx formation in the burner is usually less expensive than reducing NOx using postcombustion technology, such as SCR. Recognizing the preference for combustion controls in response to the CAAA, burner and gas turbine manufacturers embarked on an aggressive program to develop advanced combustion controls that would produce lower NOx emissions without adverse side effects. Because operation of a typical combustion burner tends to favor high NOx emissions when combustion is efficient,⁸ the development of burners that burn fuel efficiently and reliably with low products of incomplete combustion and thus with low NOx was a major technical challenge.

For large utility boilers, low NOx emissions are achieved through careful mixing of fuel and air at the point of ignition, followed by the gradual addition of air to complete the combustion process. The combustion is initially fuel rich at the ignition point and becomes fuel lean as air is added. Staging of combustion with a rich stage and then a lean stage is achieved within the burners and through combination of the burner with overfire air (OFA), which admits air downstream of the burner so that the burner may be operated in a more fuel-rich condition. Staged combustion results in longer flames because the air is admitted more slowly. This characteristic makes it more difficult to retrofit low NOx combustion controls onto existing units. However, through cooperative development programs by industry and government, combustion controls have advanced to enable substantially lower NOx emissions levels than previously thought possible through combustion controls alone. For example, units firing PRB coals have achieved controlled NOx emissions below 0.15 pounds per million British thermal units (lb/MMBtu), and units firing bituminous coals have achieved below 0.25 lb/MMBtu — solely through the use of advanced combustion controls. These emissions levels were too low to achieve with coal without postcombustion controls in the past. Innovation, in response to the need for low-cost ways to reduce NOx, is what made these results possible. It is important to note that if the rules had specified the technologies that were to be added, they would have likely required postcombustion controls only, and if they had specified the required emissions rate, they would have required a rate higher than was possible with the improved combustion and postcombustion devices.

Innovation was not limited to coal combustion. Lean premixed combustion is also possible when natural gas or other volatile, low-nitrogen fuel is burned. In lean premixed combustion, fuel and air are premixed prior to ignition. The subsequent combustion remains in a fuel-lean condition throughout the process but at temperatures sufficiently low to maintain low thermal NOx generation. This method of combustion permits the lowest possible NOx emissions from combustion of fuel and air by a flame — as low as 0.01 lb/MMBtu, or single-digit NOx emissions. As a result, this method of combustion, which was not commercially available at the time the CAAA was passed, has been of great interest to operators of gas-fired facilities (it is not applicable for coal or heavy oil). However, maintaining stable combustion is difficult using this form of combustion. Design of burners and gas turbine combustors using this combustion approach therefore posed a challenge to technology suppliers. Through development efforts by industry and government, the technical challenges associated with lean-premixed combustion have largely been addressed for most applications of interest. Lean premixed combustion is now available and is widely used on gas turbine combustors from every major gas turbine manufacturer — and U.S. turbine suppliers lead the world in this technology. Lean-premixed combustion also is used extensively on industrial boilers and process heaters in a wide range of

⁸ This is because high temperatures cause nitrogen (N₂) to break apart and combine with oxygen to form NOx, and cooling the burning fuel can lower the efficiency of the system and lead to incomplete combustion.

industries. And, similar to gas turbines, U.S. suppliers lead in this technology as well. Single-digit NO_x emissions thus are possible on a wide range of gas-fired combustion systems, and U.S. companies are selling this technology worldwide.

Turbine suppliers developed the lean-premixed combustors to avoid the cost of SCR on new combustion turbines. The advanced combustors were intended to achieve such low NO_x levels that SCR would not be able to compete. The SCR suppliers, in light of this challenge to their business, improved the performance of their product to remain viable in this market. In fact, the SCR suppliers even developed new catalysts for extremely high-temperature, simple-cycle applications, where SCR catalyst had not previously been used successfully. This is an excellent example of competitors working to secure their share of the pollution-control market that would not have existed without the regulatory impetus.

Evolution of Mercury Control Technologies

Mercury (Hg) is a toxic pollutant that is identified in Title III of the CAAA. At one time, Hg was emitted at much higher levels from municipal waste combustors (MWCs). Although efforts to reduce the amount of Hg in municipal waste have been effective at reducing Hg emissions, it was not enough. The varied nature of municipal waste and the toxic nature of Hg made postcombustion control necessary to assure low Hg emissions. Powdered activated carbon (PAC) sorbent is a technology that had been used successfully in Europe and Japan to reduce Hg emissions from MWCs. Acid gas controls, such as dry FGD with a fabric filter, also can help to reduce Hg emissions. At the time the CAAA was signed into law, however, the effectiveness of these technologies at U.S. facilities had not been demonstrated. Testing of Hg sorbent injection systems on U.S. MWCs proved effective in controlling Hg beyond what was possible from the acid gas removal system. Based on the results of that testing, a requirement to control Hg from MWCs was established that resulted in widespread adoption of this technology. By 2000, all large MWCs and most other waste incinerators were equipped with this technology to control Hg emissions.

Because mercury is also present in trace amounts in coal, it is emitted from coal-fired power plants. EPA recently issued a new Hg “cap-and-trade” rule under Section 111 of the Clean Air Act in lieu of a standard under Title III. Anticipation of this rule, called the Clean Air Mercury Rule, along with Congressional consideration of multipollutant legislation that would control Hg and other pollutants from power plants, has driven significant research and development (R&D) to develop control technologies for reducing Hg pollution. Currently, most of the Hg control for power plants comes from the “co-benefits” of SO₂, NO_x, and PM controls, and there is little, if any, use of activated carbon injection (ACI), the state of the art for Hg control in waste incineration applications.

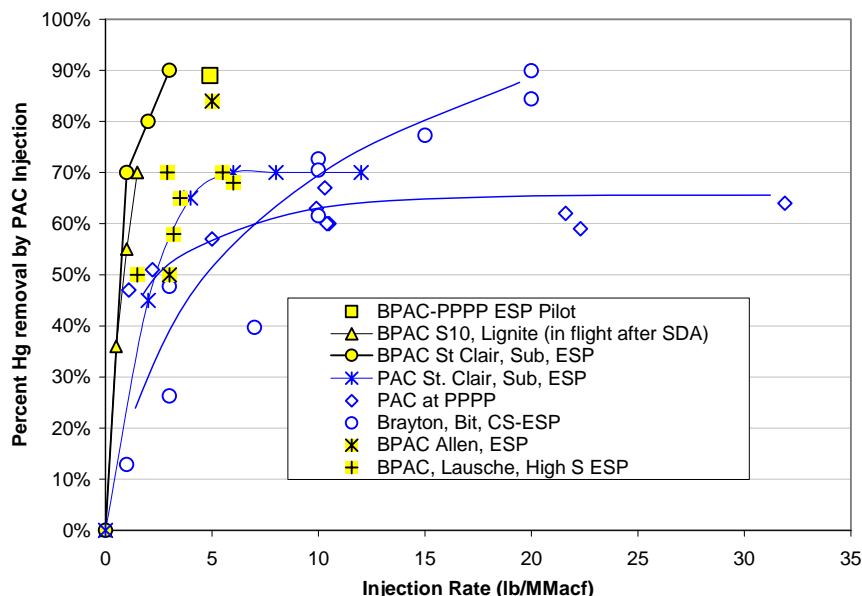
Mercury is captured to varying degrees by existing PM and SO₂ controls from the exhaust gas of coal-fired power plants. While mercury-specific controls have been deployed successfully on MWCs, the success of these technologies in controlling Hg emissions is not assured on coal-fired plants for the following reasons:

- Concentration of Hg in coal-fired power plant flue gas is much lower than for MWCs;
- The chemical form of Hg, which is less predictable for coal-fired power plants, has a significant impact on the ease of removing it;
- Capture of Hg is strongly affected by the presence of other trace elements in the flue gas, such as chlorine and SO₃; and

- Coal-fired power plants may or may not have any postcombustion controls beyond PM controls, and the type of controls has a significant impact on Hg capture.

Thus, there was reason to believe that the success in controlling Hg with sorbent that was experienced with MWCs might not be possible for coal-fired boilers.

Figure 5: Comparison of Hg Removal by BPAC and Standard PAC



Note: Comparison of Hg removal by B-PAC to that by standard PAC for injection upstream of CS-ESP; standard PAC data are with Norit FGD.⁹

Initial tests of standard PAC sorbent on flue gas from coal-fired power plants showed that its effectiveness varied significantly based upon coal characteristics, the air pollution control equipment used, and flue gas characteristics, as shown by the blue lines in Figure 5. Technology developers worked to create new technology to address this emerging market.

To provide more effective and reliable control, technology suppliers developed sorbents specially designed to address many of the shortcomings of standard PAC in coal-fired power plant flue gas. Chemically treated PAC and other advanced sorbents appear to have overcome many of the shortcomings of standard PAC and more consistent performance, as shown by the black lines and yellow background points in Figure 5. Research is underway for other sorbents that may be more effective or less expensive (or both) than activated carbon when used in utility boiler applications.

⁹ "Control of Mercury Emissions from Coal Fired Electric Utility Boilers: An Update," Air Pollution Prevention and Control Division, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC, February 18, 2005.

Newer sorbents, including halogenated activated carbon, are extremely promising, especially for coal types that had previously been considered hard to control. One such sorbent is chemically treated PAC, and field tests indicate this new sorbent's removal efficiencies can be several times that of normal activated carbon. Another is "amended silicate," which, in initial research, appears to be more effective than standard carbon without having a negative impact on the plant fly ash that may be sold for beneficial use. Another new type of sorbent, the Pahlmanite sorbent, is showing great promise in effectively removing SO₂, NO_x, and Hg simultaneously. Therefore, innovation by U.S. technology developers have advanced this promising technology for providing higher and more reliable levels of Hg capture than was possible from cobenefits of other controls or from standard PAC.

Innovation in Hg control is not limited to sorbent technology. Numerous companies are working to increase the Hg removed by existing pollution control equipment. And they are succeeding. Babcock & Wilcox developed a chemical additive that improves capture of Hg by wet FGD systems. Several U.S. companies are developing methods to control combustion in order to maximize Hg capture in downstream equipment. U.S. companies Powerspan, Enviroscub, and others have developed multipollutant control technologies that capture NO_x, SO₂, and Hg. Powerspan and First Energy of Ohio recently announced plans for a full commercial installation of the Powerspan technology (see text box). Since the U.S. is the first nation to regulate emissions of Hg from coal-fired plants, U.S. companies now lead the world in this technology. This leadership would not have been possible without a regulation that created a market for the technology.

Innovative Multipollutant Control Technologies

Promising new technologies can help reduce several pollutants simultaneously

Controlling NO_x, SO₂, PM, and mercury with one system may provide compelling economic benefits. Several technology suppliers have worked to develop means to control multiple pollutants.

One of these technologies, **Electro-Catalytic Oxidation (ECO)**, offered by Powerspan, uses a barrier discharge reactor to oxidize pollutants that are captured in a downstream ammonia scrubber. The ECO process also produces marketable fertilizer. The process demonstrated 90 percent NO_x removal, 98 percent SO₂ removal, 80 percent Hg removal, and 95 percent removal of all acid gases (such as SO₃) and fine particulate matter at First Energy's Burger plant. First Energy recently committed to install ECO at the 215 MW Bay Shore plant in Oregon, Ohio.

Another promising technology removes the pollutants from the coal before it is burned. The **K-Fuel Plus** process from KFX uses a proprietary process to improve the heating value of low-quality subbituminous or lignite coal. In addition to removing ash and moisture from the coal, thus improving the heating value, the K-Fuel process removes sulfur and Hg from the coal. NO_x emissions also are reduced when compared to substitute fuel of similar heating value, which K-Fuel is designed to replace. KFX plans to have a commercial 750,000 ton-per-year (TPY) processing facility in operation by late 2005 that will later be expanded to 8 million TPY. The process can reduce Hg content in the coal by an average of about 70 percent and NO_x and SO₂ emissions up to 30 percent. Carbon dioxide (CO₂) emission reductions also are possible due to the improved heating value of the fuel.

Other Stationary Source Controls

Controlling VOC Emissions for Ground-Level Ozone

Paints and Coatings— Section 183(e) of the CAAA and subsequent rulemakings for Architectural and Industrial Maintenance, Automotive Coatings, and Consumer Products provided the stimulus to produce low- and zero-VOC coatings and aqueous solvents for paints. Moreover, these rules provided the impetus for technological advancements in VOC-reducing catalysts that are primarily used for mobile sources, but also are used in air conditioners and car radiators. For example, Engelhard Corporation's "PremAir" catalysts convert ground-level ozone to oxygen by passing ambient air over the surfaces coated with the catalyst.

Water-Dispersible Chemical Agent Resistant Coatings

Pennsylvania Army National Guard

The Combined Support & Maintenance Shop (CSMS), east of the Pennsylvania Army National Guard has become the model for pollution prevention in the Army National Guard by replacing its solvent-borne coating with new water-dispersible Chemical Agent Resistant Coatings (CARC) for routine surface coating operations. The water-dispersible CARC emits virtually no hazardous air pollutants (HAP), and the VOC content is lower than the standard solvent-based CARC used throughout the Army, dramatically reducing emissions of these pollutants. It is estimated that switching to water-dispersible CARC will reduce VOC emissions by 2.6 tons in the first year. The transition to the less toxic water-dispersible CARC also has proved beneficial by reducing hazardous wastes and consequential disposal fees. The new CARC is more durable so it will be replaced less frequently, and it is easier to clean, reducing the use of detergents and the production of waste water. Using water-dispersible CARC reduces overspray during the coating process, which decreases the volume of paint used and the particulates emitted. Reduced overspray, along with less frequent repainting, reduces human exposure to the paint. The transition to water-dispersible CARC is particularly notable because CSMS developed this new production process without regulatory drivers and had to address operational and technical challenges as well as organizational resistance. CSMS is influencing others in the Army National Guard throughout the country to take an active role in air pollution prevention. State commands in Arizona, Oklahoma, and Rhode Island already are using systems similar to the Pennsylvania CSMS.

Source: Clean Air Excellence Awards, 2004

New and improved lower VOC and no VOC paints and industrial coatings are being developed that have the potential to reduce VOC emissions by significant amounts.

These include acrylic plastisols that can replace the more traditional polyvinyl chloride industrial coatings and provide a superior exterior durability and better environmental performance.

Super High Solids Ultra-Low Emissions Automotive Coating *DaimlerChrysler and DuPont*

DaimlerChrysler and DuPont are the first firms in the world to use a new paint technology—“Super High Solids”—an ultra-low emissions clearcoat technology. Based in part on a DaimlerChrysler challenge to reduce emissions at its Newark, DE, assembly plant, DuPont invented a clearcoat technology that increases the solid content of the paint from the industry standard of 50 percent to 65 percent. The significant increase in solids content was achieved via reduction of the molecular weight and particle size of the paint, allowing the material to behave more like a conventional liquid during the application process.

As a result of this new DuPont technology, DaimlerChrysler's coating operations in Delaware have realized a 29 percent reduction in topcoat VOC emissions, an 84 percent decrease in associated hazardous air pollutant emissions, and more than 50 percent reduction in odor potential. By implementing this technology in 2002, DaimlerChrysler not only achieved its commitment to the State of Delaware to reduce the Newark facility's topcoat emissions, but also completed it more than a year earlier than required to do so. The Super High Solids technology has broad applicability in coating operations throughout the industry. In addition to reducing emissions, the clearcoat significantly improves overall durability and aesthetics.

Source: Clean Air Excellence Awards, 2002

Solvent-Free Industrial Adhesives — Another area where significant improvements have been made to reduce VOC emissions is for industrial adhesives, including new generation solventless adhesives for the film converter industry and ultraviolet curing cold-blocking adhesives for the optical lens manufacturing industry. For example, in 1995, the Eastman Chemical Company introduced a water-dispersible hot-melt adhesive raw material, called Eastman AQ 1350, that led to significant reductions in VOC emissions. Advances in waterborne adhesives used in meat and cheese packaging plants and coffee bag lamination markets also have contributed significantly to reducing VOC emissions.

Phasing Out CFC Emissions for Stratospheric Ozone

Chlorofluorocarbons (CFC) were used in many common household goods, such as air conditioners in cars and buildings, packaging and preserving foods, and manufacturing computers and other electronic equipment. U.S. manufacturing industries consumed more than a third of the CFCs produced worldwide, and “American goods and services involving CFCs were worth \$28 billion annually, and installed equipment worth more than \$128 billion relied on CFCs.”¹⁰ However, in the late 1980s, these chemicals were identified as harmful to the

¹⁰ See Cook, Elizabeth, ed. “Ozone Protection in the United States: Elements of Success.” World Resources Institute. 1996.

protective ozone layer that shields the Earth from the sun's ultraviolet rays. As a result, an international effort to eliminate these harmful chemicals from the production process led to enactment of the Montreal Protocol in 1987 to phase out CFCs.

Building on the Montreal Protocol, Title VI of the CAAA established a comprehensive regime for phasing out all ozone depleting substances (ODS) in the U.S., including CFCs, which were some of the most damaging ODSs. Along with phase-out schedules for production of CFCs, Title VI also banned the sale and distribution of certain nonessential products containing CFCs and required manufacturers to label their products to indicate they contain or are manufactured with CFCs. These new authorities in the CAAA, along with an excise tax on sales of CFCs, and EPA's hands-on partnering with industry, facilitated the phase-out and the development of substitutes without significant economic disruption.

The excise tax on CFCs helped raise revenue and gave users a financial incentive to conserve the chemicals and adopt alternatives.¹¹ EPA also instituted a tradable consumption permit system that controlled the production and importation of CFCs and halons but left users relatively free to decide how to meet the reduction targets. This market-based approach reduced EPA's administrative costs and lowered business' record-keeping expenses and compliance costs as they searched for the least expensive compliance strategies. These policies were successful and resulted in lowering CFC consumption 35 percent below the allowable EPA limits within the first four years after implementation.

When the Montreal Protocol was signed in 1987, few alternatives to ODS were available, and industry predicted that the costs to develop such alternatives would be high and the progress slow. The collaborative relationships between industry and EPA, however, stimulated innovation and minimized the economic disruption associated with the implementation of the phase-out provisions under the CAAA and led to quick development of alternatives to CFCs. Hydrofluorocarbons (HCFCs) were relied upon initially as substitutes for CFCs when the phase-out was announced; however, as a result of their ozone depletion potential (albeit lower than CFCs), they were declared transitional. Chemical companies, such as Dow Chemical Company, Honeywell, and DuPont, began searching for alternatives to CFCs and HCFCs in the early 1990s, and successfully commercialized a number of substitutes. The Significant New Alternatives Policy (SNAP) program, created under Section 612 of the CAAA, helped chemical companies identify alternatives to Class I (CFCs, halons, carbon tetrachloride, methyl chloroform, and methyl bromide) and Class II (HCFCs) ODS.

As a result of these collaborative efforts, most products that were previously dependent on CFCs are still on the market with identical or superior performance and comparable cost of ownership. Although some ODS-free products have had an initial higher cost, they have also had greater energy efficiency, durability, and/or reliability.¹²

¹¹ The following discussion is based on Cook (1996).

¹² Andersen, Stephen O. and K. Madhava Sarma. 2002. Protecting the Ozone Layer: The United Nations History. United Nations Environment Program and Earthscan Publications: London, 2002.

III. On-Road Mobile Source Controls

Summary of On-Road Mobile Source Regulations

The Clean Air Act of 1970 was one of the earliest attempts at establishing specific responsibilities for government and private industry to reduce emissions from all sources, including mobile sources. The 1990 Amendments clarified some of the clean air goals set forth in 1970, while instituting stricter requirements to more effectively meet those goals.

To understand the evolution of the air pollution regulations from mobile sources at the federal level, one must first analyze the regulations that evolved in California. Because California had severe air quality problems, EPA granted the state authority to set its own vehicle emissions standard to confront the problem.

In September 1990, the California Air Resources Board (CARB) adopted the Low-Emission Vehicle and Clean Fuels regulations. These regulations required automobile manufacturers to introduce progressively cleaner light- and medium-duty vehicles with more durable emissions controls. The regulations established stringent emissions standards for four new classes of light- and medium-duty vehicles. Also, for the first time, an increasingly stringent annual fleet average emissions requirement was established to provide a flexible mechanism for phasing in low-emission vehicles. The four new classes of vehicles proposed were: transitional low-emission vehicles (TLEVs), low-emission vehicles (LEVs), ultra low-emission vehicles (ULEVs), and zero-emission vehicles (ZEVs). Beginning in 2003, 10 percent of the largest auto manufacturers' light-duty vehicle fleets must be comprised of ZEVs.

In 1998, CARB amended the LEV regulations and proposed LEV II. The new amendments are expected to bring further advancements in emissions reduction technology for light- and medium-duty vehicles. LEV II regulations, running from 2004 through 2010, include new regulations on sport utility vehicles and pickup trucks that currently are being used as passenger cars rather than as work vehicles. These regulations also include:

- An additional super low-emission vehicle category;
- Significantly lower NO_x emission standards;
- Increased emissions control durability standards from 100,000 miles to 120,000 miles for passenger cars and light trucks;
- Better evaporative emissions controls; and
- Introduction of partial ZEV credits for advanced technology vehicles to offset the need for building electric vehicles.

The federal government followed the lead taken by California in setting mobile source standards that have led to significant emissions reductions nationally. Recent federal standards have been effective in reducing emissions because of the ability to carry forward lessons learned in California and technological improvements in developing low-sulfur fuel.

Federal regulations regarding the reduction of mobile-source emissions fall under Title II of the CAAA. This Title applies to owners, operators, and manufacturers of mobile sources such as cars, buses, trucks, and airplanes. Examples of Title II programs include:

- Tighter tailpipe emission standards for passenger vehicles;

- Cold temperature carbon monoxide standards;
- Improved reformulated gasoline;
- Reduced diesel particulate standards for urban buses; and
- Clean fleet vehicle requirements for specific target areas across the country.¹³

Current cars emit 60 to 80 percent fewer emissions compared to cars built in the 1960s.¹⁴ However, emissions reductions gained from motor vehicle controls imposed in the 1970 Clean Air Act have largely been offset by a rapid growth in the number of vehicles on the roads and the total miles driven.¹⁵ Further, many of the devices installed in vehicles for reducing tailpipe emissions were mandated to work only up to 50,000 miles, while many cars are now driven past 100,000 miles. In addition, the mandates for curbing emissions from trucks and buses have not been as strict as for cars, even though the former emit a significant percentage of the pollution. Finally, auto fuel has become more polluting. As lead was being phased out, gasoline refiners changed gasoline formulas to make up for octane loss, and the changes made gasoline more likely to release VOCs into the air.¹⁶ Section V discusses the changes in clean fuels technologies as a result of the 1990 Amendments.

Cars and trucks account for nearly 50 percent of ozone precursors, NO_x, and VOC, and up to 90 percent of carbon monoxide (CO) in urban areas.¹⁷ Due to this unanticipated growth in mobile source emissions, the CAAA instituted stricter emissions reduction strategies. These new standards, from the time they were phased in beginning with the 1994 model year, began helping to reduce tailpipe emissions of hydrocarbons, CO, and NO_x. Automobile manufacturers also are required to reduce vehicle emissions resulting from the evaporation of gasoline during refueling.

Innovations in Mobile Source Technologies

EPA followed CARB's LEV II rule with the introduction of Tier 2 standards for light-duty vehicles. These standards required a 90 percent reduction in NO_x emissions from light-duty vehicles and a synchronization of light-duty truck standards with light-duty passenger car standards. In addition, Tier 2 regulations required lower sulfur gasoline to be sold in the U.S., which facilitated further catalytic control advances in automotive emissions control. The improvements included better fuel control, faster catalyst light-off, better evaporative emissions control, and a tighter PM standard for light-duty diesel vehicles.

Prior to these rules, Tier 1 light-duty passenger cars and some light trucks were using three-way catalysts with some form of feedback controlled fuel system to maintain stoichiometry (i.e., the precise fuel-to-air ratio where sufficient oxygen is supplied to completely combust the fuel). Although the three-way catalysts were fairly effective in reducing NO_x and VOC emissions from running engines, cold start emissions became significantly more important. In addition, emission control system degradation was an issue that needed addressing. With Tier 1 and 2 federal standards and California's LEV I and II programs, catalyst formulations became more sophisticated, taking advantage of layering. More refined substrates with more cells per square inch were manufactured to provide greater catalyst surface area in a smaller package. In addition, rare earths formulations were improved to retain and release oxygen at the proper

¹³ http://www.transource.org/shared_files/htm/clean_air_act.htm

¹⁴ http://www.epa.gov/oar/oaqps/peg_caa/pegcaa04.html#topic4

¹⁵ <http://www.epa.gov/oar/caa/overview.txt>

¹⁶ http://www.epa.gov/oar/oaqps/peg_caa/pegcaa04.html#topic4

¹⁷ Ibid.

time. Catalyst companies started making agreements with platinum mines to minimize price swings for precious metals. Precatalysts were used for quick heat up to reduce cold start emissions.

On the fuel control side, faster and more powerful computers allowed quicker and more precise feedback control. Improved sensors such as heated oxygen sensors provided quicker reaction times and significantly reduced warm-up time. On-board diagnostic systems, which indicate if a sensor or other important emissions control component has malfunctioned, became commonplace. More precise fuel control led to better catalyst efficiency and therefore lowered emissions. As lessons were learned on light-duty vehicles, the technology was transferred, first to light trucks, and then to heavy gasoline trucks. Emissions control on gasoline vehicles is now near zero emissions levels in passenger cars and very low levels in light- and heavy-duty gasoline trucks.

The Heavy-Duty Engine standards starting with the 2007 model year will significantly reduce NOx and PM emissions from heavy-duty trucks and buses. These standards include a requirement to sell ultra-low sulfur diesel fuel in the U.S. starting in 2006. The ultra-low sulfur diesel fuel enables the use of after-treatment devices (NOx absorbers and catalysts, particulate filters, and oxidation catalysts), which significantly reduce emissions from diesel engines.

Prior to 1990, heavy-duty diesel engines were essentially uncontrolled. With the 1990 Amendments, diesel emissions levels were regulated, with the 2010 levels representing a 98 percent reduction in NOx emissions and a 99 percent reduction in PM emissions over pre-1990 engines. As part of the 2007/2010 heavy-duty diesel engine regulations, significant reductions in fuel sulfur levels also were established, and this allowed the use of after-treatment on diesel engines. Significant breakthroughs have occurred on lean NOx catalysts through better precious metal formulations. In addition, active regenerating particulate filters have allowed use of particulate filters on engines that would not generate enough exhaust temperature to regenerate sufficiently.

Several standards have also led to improvements in automotive technology that were not formerly envisioned. For instance, the original CARB LEV I regulations were assumed to be met with alternative fuel vehicles. Improved gasoline and catalyst technology produced gasoline vehicles that competed with alternative fuel vehicles in terms of reduced emissions. CARB's Zero Emission Vehicle program, while not resulting in market

Getting in Gear: Transforming Truck Technology in America *Environmental Defense, FedEx Express, and Eaton Corporation*

Environmental Defense, FedEx Express, and Eaton Corporation partnered to bring a cleaner hybrid truck to the market, initiating a powerful transformation of the truck market with cleaner technology. As of March 2005, 18 low emissions preproduction hybrid electric-powered delivery trucks, provided by Eaton Corporation, were placed into service. Assessed against the standard delivery vehicle in the FedEx fleet, the hybrid truck will reduce smog-causing NOx emissions by 65 percent, decrease particulate emissions with the aid of a diesel particulate trap by 96 percent, reduce emissions of greenhouse gases by 37 percent, and achieve a fuel economy gain of 57 percent. If reliability and cost-effectiveness goals are met, FedEx will take steps to introduce more of the vehicles into its fleet over time and can make them a standard replacement vehicle in its weight class of 30,000 medium-duty trucks. If FedEx begins replacing its fleet, then smog-causing NOx pollution will be reduced by 2,000 tons a year for every 10,000 conventional FedEx trucks that are replaced by new hybrids. This reduction would be the equivalent of taking all passenger cars off New York City roads for one month. Hybrid technology is not proprietary to FedEx, so it can be applied throughout the industry in fleets across the country. Unlike alternative fuel or pure electric vehicles, this hybrid truck uses a standard diesel engine, eliminating the need for developing additional fueling infrastructure and removing the need to be plugged in.

Source: Clean Air Excellence Awards, 2004

penetration by pure electric vehicles, helped improve and perfect electric motors and controllers that are currently being used on hybrid electric vehicles. Future uses of this technology will include plug-in hybrids and fuel cell vehicles.

Future Changes for Mobile Sources

Apart from the changes for mobile sources that have already been implemented as industry tries to meet the requirements of the CAAA, significant reductions in tailpipe emissions are expected in the near future through innovations in various postcombustion (after-treatment) technologies in the 2007 to 2010 timeframe for gas and diesel light-duty trucks and cars.

NOx Absorbers -- These absorbers will reduce NOx emissions substantially in a lean exhaust environment, storing NOx emissions and then reacting them in a rich environment by injecting additional unburned fuel into the exhaust stream before a NOx reduction catalyst.

Particulate Filters -- These filters will reduce PM emissions substantially in diesel vehicles by storing harmful soot emissions on a filter and then burning the carbon soot to create CO₂ during higher load conditions.¹⁸

Oxidation Catalysts -- Oxidation catalysts will reduce CO, VOCs, and NOx substantially on diesel engines. Gasoline engines already have three-way catalysts that substantially reduce these emissions.

Other Catalysts That “Eat Up” Ozone -- Platinum catalyst surfaces are applied to the vehicle radiator to remove ground-level ozone.

Electric/Hybrid Cars -- Electric/hybrid cars provide significant fuel economy and emissions benefits because they employ a smaller gasoline engine in concert with an electric motor. In addition, the higher load needs of the vehicle are offset by the electric motor, thereby reducing emissions levels from the vehicle.

Fuel Cells -- Fuel cell technology can offer zero tailpipe pollutant emissions if the fuel cell runs directly on hydrogen. Hydrogen storage on vehicles and fuel cell cost are still major issues before fuel cell technology can become widespread.

Alternative Fuels -- Alternative fuels include methanol, ethanol, propane, natural gas, hydrogen, and electricity. Current research focuses on improving the performance of cleaner fuels, utilizing more abundant or renewable fuels like ethanol, natural gas-derived fuels, and biodiesel, and modifying current fuels to make them cleaner by adding ethanol to gasoline as an oxygenate.

Vehicle/Engine Improvements -- Significant progress in engine design has taken place in recent years and is continuing. The improvements include variable valve timing, electrically operated valve trains, improved sensor technology, improved fuel injection technology, and improved oil control. Improvements in engine technology increase engine efficiency while reducing emissions. Vehicle aerodynamic improvements also reduce fuel consumption and emissions by reducing the load needed to move the vehicle down the road.

¹⁸ Although primary PM is not a first-order factor in ozone formation, it indirectly affects the effectiveness of ozone controls, because frequently there is a trade-off between NOx and PM controls (i.e., PM increases as NOx decreases), necessitating additional PM controls.

IV. Off-Road/Nonroad Mobile Source Controls

Summary of Nonroad Mobile Source Regulations

Nonroad vehicles include locomotives, recreational, farm, and construction vehicles. All nonroad vehicles are subject to regulation under the 1990 Amendments. Air emissions from locomotives must be reduced; however, for other nonroad vehicles, EPA must issue regulations if a study shows that controls would help reduce pollution.¹⁹ Specifically, Congress required EPA to conduct studies on certain nonroad engines to determine if NO_x and VOC emissions contributed significantly to ozone and CO pollution. The following are EPA's categories of nonroad vehicles operated by engines using a range of fuels for operation (e.g., diesel, natural gas, propane, and gasoline):

- *Large Industrial Spark-Ignition Engines:* Nonroad engines that are powered by gasoline, liquid propane gas, or compressed natural gas rated over 19 kW (25 horsepower). These engines are used in commercial and industrial applications, including forklifts, electric generators, airport baggage transport vehicles, and farm and construction vehicles.
- *Recreational Vehicles:* Snowmobiles, off-highway motorcycles, and all-terrain vehicles (ATVs).
- *Diesel Marine Engines:* Diesel engines over 37 kW (50 horsepower) used in recreational boats.

Innovations in Nonroad Source Technologies

The Tier 3 emissions standards for nonroad diesel engines were established in 1998. They significantly reduced NO_x and VOC emissions from 50 to 750 horsepower diesel engines used in agricultural and construction equipment. To accomplish the required reductions in emissions, technology advancements from highway diesel engines were used on nonroad engines, including the following:

- Charge air cooling;
- Fuel injection rate shaping and multiple injections;
- Exhaust gas recirculation;
- Better fuel/air control; and,
- Diesel oxidation catalysts.

Additions to the nonroad diesel engine rules included diesel marine engines. Improvements in these engines featured separate circuit after-cooling to reduce NO_x emissions, as well as better fuel control, higher pressure injection, and engine modifications for better emissions.

¹⁹ <http://www.epa.gov/otaq/largesi.htm>

The Large Industrial Spark Ignited (SI) engine rule required emissions reductions from large industrial spark ignited engines such as those used in forklifts, electric generators, and airport baggage handling equipment, recreational engines used in snowmobiles, off-road motorcycles, ATVs, and diesel marine engines used in recreational boats, yachts, and cruisers. Improvements in spark ignition technology included better fuel control, on-board diagnostic systems, and catalysts. Diesel marine engine improvements featured separate circuit after-cooling to reduce NOx emissions, as well as better fuel control, higher pressure injection, and engine modifications for reduced emissions. These changes are expected to bring about an overall 72 percent reduction in hydrocarbon emissions, an 80 percent reduction in NOx emissions, and a 56 percent reduction in CO emissions in 2020.

Small SI engine rules currently are being developed to reduce emissions from such sources as lawn mowers, utility generators, and spray washers. High hydrocarbon and emissions from these engines make them a noticeable source during summer months.

Improvements include better engine cooling and oil control, movement from side valve to overhead valve engines, better

gaskets and fuel control, and use of catalysts in commercial use models. In addition, improved gas can material reduces emissions that recur daily from gasoline stored in cans.

Evinrude® E-TEC™ Clean Air Technology
Bombardier Recreational Products, Inc.

In 2003, Bombardier Recreational Products Inc. (BRP) introduced Evinrude E-TEC, the cleanest outboard engine for marine recreational products, which is based on two-stroke engine technology. Compared to a similar state-of-the-art 2004 four-stroke engine, CO emissions from the Evinrude E-TEC are typically 30 to 50 percent lower and at idle are lower by a factor of 50 to 100 times. In addition, Evinrude E-TEC emits 30 to 40 percent less total PM on a weight basis than a similar "ultra-low emissions" four-stroke outboard. Furthermore, NOx and hydrocarbon emissions for Evinrude E-TEC are similar, if not lower, than a four-stroke outboard.

In addition to air quality benefits, Evinrude E-TEC engines are uniquely designed. There are no oil changes with this engine, as well as no belts, and no valve or throttle linkage adjustments. Numerous advancements combine to create the Evinrude E-TEC quiet sound, including an exclusive idle air bypass circuit. This advanced new Evinrude E-TEC technology offers environmental benefits and has enormous potential outside the marine industry.

Source: Clean Air Excellence Awards, 2004

V. Clean Fuels

Summary of Regulations for Clean Fuels

The Clean Air Act of 1970 and the Amendments of 1990 had a significant impact on the petroleum refining industry, both in terms of refining processes and the formulation of refined products.²⁰ The 1970 Act required a gradual reduction of lead in gasoline and a complete elimination of lead by the mid-1980s, as well as reductions in sulfur levels in the residual and distillate fuel oils used by electric utilities and industrial plants. The 1990 Amendments called for reformulation of motor fuels under Section 211 and placed a limit on the sulfur levels in diesel to reduce air emissions from mobile sources. Some of the key regulations in the CAAA, Section 211, are:

- From October 1, 1993, diesel fuel for on-highway use will not contain sulfur above 0.05 percent or 500 parts per million (ppm) by weight. Prior to this regulation, there was no limit on sulfur levels in motor fuels, and the sulfur level in diesel was around 2,000 ppm.
- The Oxygenated Fuels Program under the CAAA required that all gasoline sold in 39 CO nonattainment areas have a minimum of 2.7 percent oxygen (by weight) for at least four winter months, by November 1992.
- The Reformulated Gasoline Program (RFG) required the use of regulated gasoline formula by January 1, 1995, in nine U.S. metropolitan areas with the worst ground-level ozone problems. The RFG requirements are a minimum of 2 percent by weight oxygen content and maximum benzene content, an aromatic compound of 1 percent by volume, and no lead or manganese. A more complex RFG formula was adopted in 1998 to further reduce emissions.
- Refiners were also required to comply with tighter Reid Vapor Pressure (RVP), a measure of volatility, regulations in effect under the VOC standards of the 1990 Amendments. These standards required a maximum RVP of 9 pounds per square inch (psi) in gasoline during the high-ozone season from 1992 onwards, down from a maximum level of 11.5 psi prior to June 1, 1989.

Innovations in Refinery Technologies Due to CAAA

Among other innovations in petroleum refining technologies spurred by the CAAA were significant technological strides made for two important processes that primarily reduced the sulfur content in fuel. These two technological changes related to diesel desulfurization and Fluid Catalyst Cracking (FCC) technologies. The following section traces their development related to the CAAA.

²⁰ 'Energy and Environmental Profile of the U.S. Petroleum Refining Industry,' Office of Industrial Technologies, Energy Efficiency and Renewable Energy, U.S. Department of Energy, December 1998.

Desulfurization for Clean Fuels

The 1970 Clean Air Act required lower sulfur in residual and distillate fuels for industrial use, which spurred the development of desulfurization units in refineries. The subsequent limits for on-highway diesel fuels under Section 211 of the CAAA accelerated this development. The traditional method of removing sulfur from oil was a process called “hydro-desulfurization,” also known as “hydro-treating.” This technology has been around since the 1930s and uses a catalyst to break down sulfur compounds under high pressure hydrogen and elevated

temperatures, forming hydrogen sulfide gas.²¹ The CAAA required that the sulfur level in on-highway diesel fuel should not be more than 500 ppm by 1993, down from an average of 2,000 ppm in prior years. In 2000, this was further revised to require sulfur levels to be no more than 15 ppm by June 2006. These lower levels created opportunities for process modifications, and new technologies emerged in recent years to meet the challenges of achieving the low sulfur standards set by the CAAA. Below are a few examples of these developments:

Ultra Low Sulfur Gasoline

Irving Oil

In the late 1990s, Irving Oil, working with North America’s leading automakers, recognized that sulfur content in gasoline causes significant environmental problems. Sulfur in gasoline decreases the efficiency of emission control systems, which results in significantly higher vehicle emissions. Irving Oil planned and made the necessary investments to address these issues and to reduce the sulfur content in its gasoline. In 2000, the company completed a two-year, \$1 billion upgrade to the Irving Oil Refinery, focusing particularly on the Residue Fluid Catalytic Cracking Complex, which provides the refinery with the ability to increase production of higher value and more environmentally advanced transportation fuels, such as low sulfur gasoline. In October 2000, the Irving Oil Refinery became the first refinery in North America to commission a full-scale CDTech[®] gasoline desulfurization technology. Thanks to these investments, Irving Oil’s low sulfur gasoline met the 2004 EPA sulfur standards more than three years ahead of schedule. Today, Irving Oil sends more than 150,000 barrels of gasoline per day into the northeastern U.S. market from its refinery. Irving Oil anticipates meeting the 2006 EPA sulfur standards ahead of schedule.

Source: Clean Air Excellence Awards, 2002

- **Sulfur Adsorption** — One new technology for sulfur removal is the “S Zorb” technology developed by ConocoPhillips. S Zorb Sulfur Removal Technology uses a proprietary sorbent that attracts sulfur-containing molecules and then removes the sulfur atom from the molecule. The sulfur atom is retained on the sorbent while the hydrocarbon portion of the molecule is released back into the process stream. Hydrogen sulfide is not released into the product stream and therefore prevents recombination reactions of hydrogen sulfide and olefins to make mercaptans, which are a group of sulfur-containing organic chemical compounds that would otherwise increase the effluent sulfur concentration.²² According to the company, this technology has been in operation at two of ConocoPhillips refineries and produces fuels with sulfur levels as low as 10 ppm.²³

²¹ ‘Cutting the cost of sulfur removal,’ Environmental Science & Technology Online, July 24, 2003, http://pubs.acs.org/subscribe/journals/esthag-w/2003/jul/tech/be_sulfur.html.

²² Technology Solutions, ConocoPhillips, http://www.coptechnologysolutions.com/sulfur_removal/szorb/advantage/index.htm.

²³ Technology Solutions, ConocoPhillips, http://www.coptechnologysolutions.com/sulfur_removal/szorb/szorb_action/index.htm.

- **Sulfur Oxidation** — This process takes a different approach to sulfur removal than the conventional hydro-treating. It creates a petroleum and water emulsion in which hydrogen peroxide is used to convert the sulfur in sulfur-containing compounds to sulfone.²⁴ The oxidized sulfone is then separated from the hydrocarbons for postprocessing. Most of the peroxide can be recovered and recycled. Major advantages of this technology include low cost, lower reactor temperatures and pressures, short residence time, zero emissions, and no hydrogen requirement.²⁵ One such sulfur oxidation process has been demonstrated by UniPure, called ASR-2, and has achieved sulfur levels of 5 ppm or less.²⁶
- **Catalysts** – Catalysts have been one of the key tools for refiners to meet the product specifications required by environmental laws. Much of the refining industry's success in meeting these challenges can be attributed to advancements made in catalysts over the past four decades.²⁷ Classical gas oil desulfurization catalysts are capable of producing diesel fuel to the required specifications; however, they deactivate rapidly due to the high-severity operations. New generation catalysts have been introduced that overcome these problems and allow for greater sulfur removal. With high active-metal loadings, improved pore structure and more coke tolerance have been introduced for deep desulfurization. For example, the conventional catalysts used for diesel desulfurization, such as Co-Mo/Al₂O₃²⁸, have been succeeded by such new generation catalysts as High metal Co-Mo/Al₂O₃ with modified pore structure to produce diesel with less than 500 ppm sulfur. Another technology, biodesulfurization, uses bacteria as a catalyst to remove sulfur from feedstock instead of the conventional materials.

Fluidized Catalytic Cracking (FCC) Technology

FCC technology is one of the primary technologies used in refineries to upgrade heavy oil into lighter products and provide high octane ratings for gasoline. This technology remains a cost-effective method for this purpose. The CAAA introduced the RFG that required low aromatic content in gasoline. The conventional FCC process produced a significant amount of extra aromatics that must be removed and/or saturated with hydrogen to produce acceptable low-aromatic gasoline or diesel. To meet the needs of the CAAA, new catalysts and process parameters were developed to produce fuels with lower aromatic and sulfur content through the FCC.

²⁴ Sulfone is any of the various sulfur-containing organic compounds having a bivalent radical SO₂ attached to two carbon atoms.

²⁵ *The Transition to Ultra-Low-Sulfur Diesel Fuel: Effects on Prices and Supply*, Energy Information Administration, SR/OIAF/2001-01, May 2001, pp. 16–17.

²⁶ R. E. Levy, A. S. Rappas, S. J. Decanio, V. P. Nero, *UniPure's ASR-2 Desulfurization Process Provides Cost-Effective Solution for Ultra-Low-Sulfur Refined Products*, World Refining, May 2001. pp. 24–32.

²⁷ M. Absi-Halabi, A. Stanislaus, and H. Qabazard, "Trends in Catalysis Research to Meet Future Refining Needs," *Hydrocarbon Processing*, February 1997, pp. 45–55.

²⁸ Co = Cobalt (Metal), Mo = Molybdenum (Metal) and Al₂O₃ = Aluminum Oxide (Compound). This catalyst is also known as the "Cobalt-Moly Desulfurization Catalyst."

Development of Alternative Fuels

During the energy crisis in the 1970s, the U.S. looked for other fuels for transportation to reduce dependency on foreign oil. Alternative fuels are inherently cleaner than gasoline because they are chemically less complex and burn cleaner. When used with advanced engine and emissions control technologies, alternative fuels burn more efficiently because they are chemically less complex and thus release fewer emissions from incomplete combustion. In addition, because alternative fuels evaporate less readily than gasoline, there are fewer evaporative emissions from the vehicle's tank, limiting smog-forming emissions.

Alternative fuels include methanol, ethanol, propane, natural gas, hydrogen, and electricity. Methanol vehicles were first introduced into California in the early 1970s in demonstration fleets, with flexible fuel vehicles starting in the 1980s. Flexible fuel vehicles enable the vehicle to run on pure gasoline, pure methanol (or ethanol), or any mixture in-between. Because of credits to manufacturer's corporate average fuel economy (CAFE) for using alcohol fuels under the Alternative Motor Fuels Act (AMFA), manufacturers began building complete lines of flexible fuel vehicles. Unfortunately, a price spike in methanol spot prices in the early 1990s ended the methanol program, and most of the stations that provided methanol to the public closed down. Manufacturers stopped building methanol flexible fuel vehicles in the mid-1990s and instead, began building ethanol flexible fuel vehicles. Unfortunately, due to the high price of ethanol and its limited availability outside the Midwest, ethanol is not used in most of the flexible fuel vehicles on the road.

Reduction of Tailpipe Emissions -- Biodiesel and Electric Vehicles ***U.S. Postal Service***

Four years ago, the U.S. Postal Service (USPS) began using biodiesel, a renewable fuel made from agricultural products, to partially replace diesel at some of its refueling sites. The biodiesel is used in a blend, B20, which is made up of 20 percent biodiesel and 80 percent regular diesel. Partnering with the Defense Energy Support Center, the USPS now purchases B20 in bulk. In 2002, the USPS used about 670,000 gallons of B20, which resulted in a 20 percent emissions reduction of CO₂ and sulfur oxides, a 14 percent reduction of hydrocarbons, a 9 percent reduction of CO, and an 8 percent reduction of PM.

In another effort to reduce its fleet emissions, the USPS purchased 500 new zero emission, battery-powered vehicles. The battery-powered vehicles are ideal for the short, stop-and-start carrier routes, reducing noise and air pollution otherwise generated by gas- or diesel-powered vehicles. This purchase provides other fleets and the public with a visible example of the applicability of electric vehicles for significant hauling and delivering tasks. The zero-emission vehicles are being used in large metropolitan areas where emissions reductions are most needed, including Washington, DC, New York City, and several areas in California. The USPS estimates that the use of these vehicles will lead to annual reductions in tailpipe emissions of CO₂ (4.8 million pounds), CO (140,000 pounds), and NO_x (10,000 pounds).

Source: Clean Air Excellence Awards, 2002

Natural gas vehicles, on the other hand, had backing from the natural gas utilities and have been trying to establish a hold. Lack of fueling stations, long fill times, and limited range have restricted the growth and purchase of natural gas vehicles outside of utility and government fleets. Use of natural gas in transit buses is becoming more widespread, but diesel technology is competitive because it is surpassing natural gas emissions levels as early as 2007. Concern about microfine particulates and toxic emissions from natural gas engines has forced the industry to use catalysts to reduce those emissions.

VI. Other Innovations

Other innovations that made improved air pollution control technologies possible include Computational Fluid Dynamic (CFD) software (and availability of lower cost computers) and advanced controls and instrumentation. CFD software is special engineering software that enables engineers to calculate various complex processes that occur in a power plant, including heat transfer, chemical reactions, and fluid flow. The CFD software therefore permits design and simulation of combustion system operation on a computer. This allows designs to be developed much more quickly and less expensively than was possible before CFD software was available. CFD software makes it possible to develop air pollution control systems that offer improved performance, better reliability, and at a lower cost.

Advanced controls have been essential parts of these improved pollution control systems. For example, operating a burner under low NO_x conditions is inherently less stable than under high NO_x conditions. To have a stable low NO_x flame under a wide range of operating conditions, it is necessary to sense a change in conditions, determine the proper adjustment, and make that adjustment quickly and accurately. Without advanced control systems, it would be impossible to control the flame for stable operation over a wide range of conditions.

Another example is FGD, a complex chemical process that has hundreds of components, such as pumps, nozzles, dewatering systems, material handling systems, agitators, and spargers. Controlling these various components to maintain the right chemical mix to reliably achieve high SO₂ removal with low reagent consumption cannot be achieved consistently without the help of advanced control systems. With any of these complex control systems, it is also possible to have the computer automatically “learn” from the operation so that the control system can continually find better ways to operate the plant and automatically determine improved operating setpoints for the future. These advancements in controls have enabled air pollution control hardware to operate at higher performance, and these controls also have the ability to improve the operation further through sophisticated learning technologies.

Advancements in materials have facilitated improvements in emissions control technologies as well. Two areas where materials science have been important are related to NO_x control, especially with respect to NO_x reduction catalysts, and SO₂ control, especially with respect to use of corrosion-resistant materials. SCR technology has been made reliable and cost effective through advancements in catalytic materials. To promote the proper reactions, catalysts must have several important physical and chemical properties: well controlled porosity; high surface area; resistance to erosion; mechanical, chemical and thermal stability; and specific chemical properties on the surface of the catalyst. The development of catalysts possessing all of the necessary characteristics reliably under challenging power plant conditions has required significant R&D investments by the major catalyst suppliers, including the market-leading U.S. firms. With regard to FGD, corrosion resistance is critical because the capture of SO₂ in an FGD system creates an acidic solution. Moreover, scaling can be a problem in the process of neutralizing that solution. Therefore, FGD components must be very resistant to acidic corrosion and scaling. Modern FGD systems use an array of corrosion resistant materials, including special alloy steel, fiberglass reinforced plastic, and coated steels.

VII. Growth of the Pollution Control Industries

Anecdotal evidence suggests that the overall level of investments in pollution control has been quite significant over the years. For example, according to a report by EPA in 1990, total investment for pollution control (across *all* media -- air, water, and land) was about \$115 billion in 1990, or more than 2 percent of the Gross National Product.²⁹ The total investment in pollution control across all media in 1990 was approximately four times higher than the \$30 billion spent in 1972. Out of this total, a substantial portion was invested to implement the programs authorized under the Clean Air Act, and the following sections focus on the investments made for air pollution control costs only.

Revenue Growth in Air Pollution Control Industry

Analyzing Growth By Type of Sources

The annualized costs of *air* pollution control have been increasing steadily ever since the passage of the Clean Air Act in 1970. Total cost more than tripled from about \$8 billion in 1972, to more than \$27 billion in 1987. Out of this, the amount spent on stationary sources has gradually declined, with a corresponding increase in the resources spent on mobile sources.

**Table 2: Historical Annualized Air Pollution Control Expenditures
(1986 \$ MM)**

Program	Year			
	1972	1980	1987	2000 ¹
Stationary Sources	6,230	13,298	18,960	29,725
Mobile Sources	1,345	4,010	7,469	14,140
Undesignated Sources	341	327	250	184
Total²	7,934	17,854	27,006	44,945

¹2000 data are projected based on a 1990 study.

²Total also includes spending on radiation programs, which constituted less than 2 percent of the total in each year.

Source: *Environmental Investments: The Cost of a Clean Environment*. EPA, December 1990.

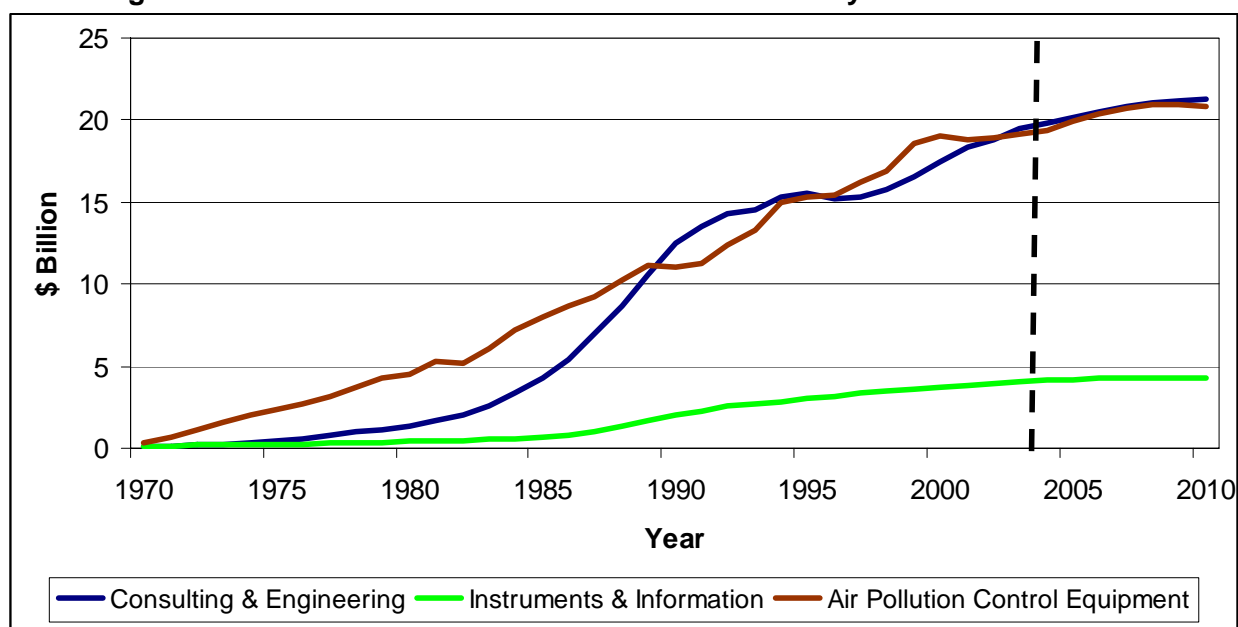
According to EPA estimates in 1990 as shown in Table 2, spending on stationary source programs was about 79 percent of the total spent on air pollution control in 1972 but went down to about 70 percent in 1987 (and was projected to go down even further to 66 percent in 2000). Spending on mobile sources were increasing in this period from about 17 percent of the total for air pollution control in 1972 to about 28 percent in 1987 (and was projected to increase further to about 31 percent in 2000). Note that the projected increase in air pollution control costs for 2000 was driven by the estimated increased expenditures needed to address the CAAA.

²⁹ See "Environmental Investment: The Cost of a Clean Environment." US EPA-230-12-90-084. December 1990.

Analyzing Growth in Control Technology Markets

Figure 6 presents the data on historical and forecast revenues for the U.S. environmental markets for the sectors associated with pollution control. The Air Pollution Control Equipment revenues include revenues from both stationary and mobile source equipment suppliers. Consulting and Engineering and Instruments and Information include both air and water media. These sectors experienced substantial growth after the 1970 Clean Air Act and experienced continued growth through the period following the CAAA. According to *Environmental Business Journal*, total exports of air pollution control equipment (stationary and mobile sources) in 2003, was \$2.65 billion of the total \$19.1 billion in revenues. The industry employed 127,400 people, and the average revenue per employee was \$150,000.

Figure 6: Environmental Market Revenues – Stationary and Mobile Sources



Source: *Environmental Business International, Inc.*

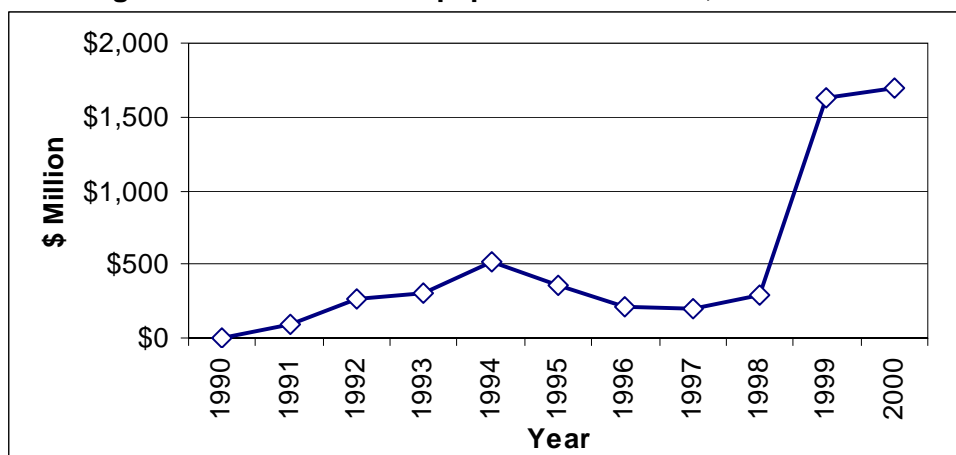
Data from 2004 onwards are based on EBI's projections (denoted by the dotted vertical line in the figure).

According to data provided by the Institute of Clean Air Companies, the trade association that represents manufacturers of stationary source air pollution control equipment in the U.S., the market for most stationary source air pollution control equipment rose domestically over the 1990–2000 time period. Figures 7, 8, 9, and 10 show revenues for NO_x Control Equipment, SO₂ Control Equipment, VOC Control Equipment, and Continuous Emission Monitoring Systems (CEMS), respectively.

As shown in Figure 7, NO_x control equipment experienced the first surge of around \$500 million in 1994. This growth largely resulted from the need for low NO_x combustion systems in response to requirements under Title IV, BACT, and LEAR for new sources, and SCR systems installed on California power plants to meet NAAQS. A rapid increase in NO_x control revenues that eclipsed this earlier peak -- at more than \$1.5 billion -- was experienced later in the decade as suppliers installed SCR systems on coal-fired boilers and on gas turbines. The SCRs on coal-fired boilers (see Figure 3 above) were a direct result of the NO_x SIP Call which stemmed

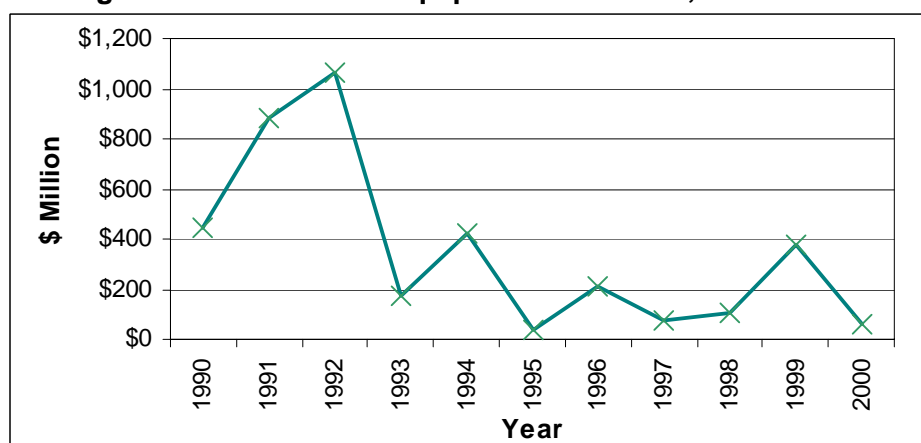
from Title I of the CAAA. According to the Edison Electric Institute, the utility industry will have spent more than \$10 billion on SCR by the time the effort for SIP Call compliance is complete.³⁰ Many of the gas turbine SCRs were necessary because new SCRs were installed in nonattainment areas, and Title I requirements forced the new turbines to achieve the lowest achievable emissions rates.

Figure 7: NOx Control Equipment Revenues, 1990 to 2000



In the 1990–2000 period, SO₂ Control Equipment Revenues experienced an early peak of about \$1 billion in 1992 as companies installed FGD in advance of the Title IV Phase I implementation, while subsequent installations during the remainder of the decade were lower. However, FGD installations are expected to pick up significantly due to CAIR and Title IV Phase II requirements.

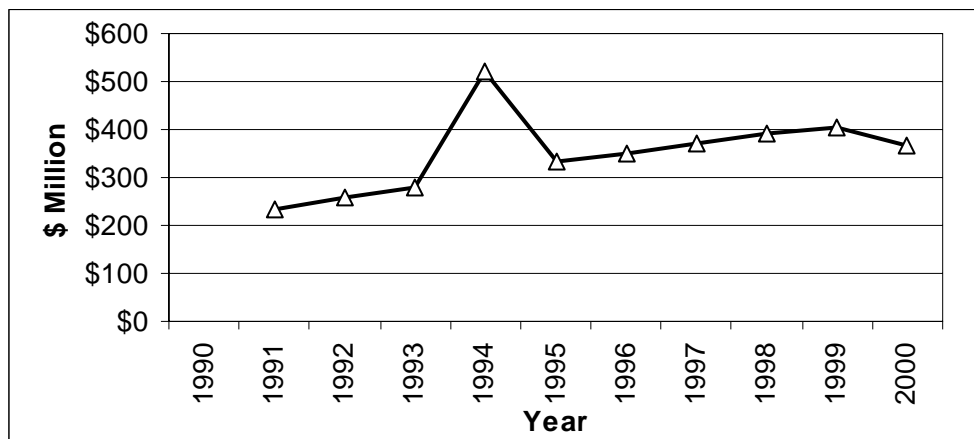
Figure 8: SO₂ Control Equipment Revenues, 1990 to 2000



³⁰ Statement of the Edison Electric Institute Hearing on S. 131, Clear Skies Act of 2005 Senate Environment & Public Works Committee February 2, 2005, http://www.eei.org/about_EEI/advocacy_activities/Congress/050202_SenateEPWstatement.pdf.

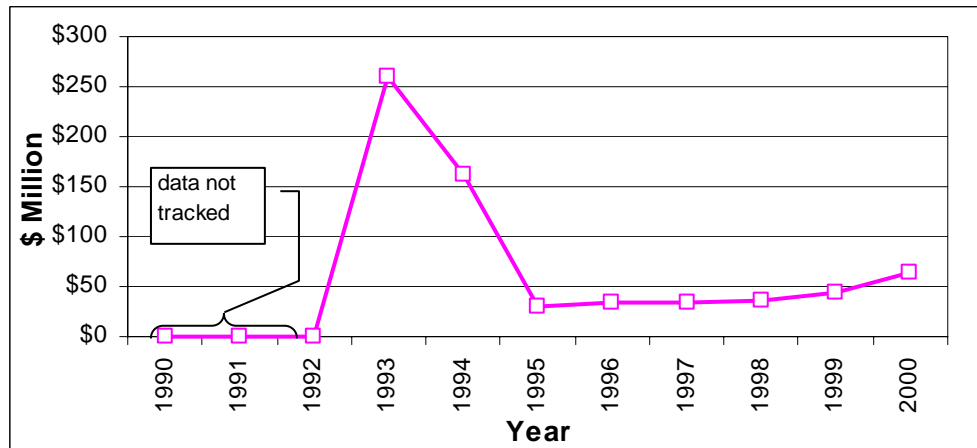
Sales of VOC Control Equipment peaked in the 1994 timeframe in response to Title I requirements. Otherwise, sales of VOC control equipment increased slowly over the decade, achieving near \$400 million in revenues in the late 1990s.

Figure 9: VOC Control Equipment Revenues, 1990 to 2000



Sales of CEMS peaked in the 1993–94 time period as utilities installed CEMS for Title IV compliance. But CEMS installations continued after the initial Title IV requirement because CEMS have become important for monitoring to comply with other parts of the CAAA.

Figure 10: CEMS Equipment Revenues, 1990 to 2000



Employment Growth

Although the growth of the pollution control industries meant that it provided employment to a significant part of the labor force, research on these employment levels seems to be inadequate. Anecdotal evidence exists as to the number of people working in fields related to pollution control. According to the U.S. Department of Commerce's International Trade Administration (ITA), the U.S. environmental technologies industries employed more than 1.6 million people in 2002.³¹ Also, as noted above, the *Environmental Business Journal* suggests that there were 127,400 people employed directly in air pollution control equipment manufacturing (both stationary and mobile sources) in 2003.

The total economic impact of the jobs supported by the environmental technologies industries in general, and the air pollution control industries in particular, is more than what these numbers suggest. Manufacturing pollution control equipment, for example, requires inputs from other supporting industries, resulting in *indirect* employment in upstream industries. Moreover, spending by the employees working in the environmental technologies industries supports additional employment in the service sectors, such as wholesale and retail trade. These secondary effects give rise to indirect jobs in industries that are connected to the environmental technologies industries by the interlinkages between different industrial sectors. Economists refer to these additional jobs as the "multiplier effects" of the direct jobs.

For example, according to an EPA study, for every direct employment sustained by the environmental technologies industries, the economy also created another indirect job in the upstream industries (for a multiplier effect equal to 2).³² Table 3 presents the estimated employment levels for the environmental technologies industries using data from the EPA study.

Table 3: Economy-Wide Employment in Environmental Technologies Industries

	1977	1982	1985	1988	1991	2002 ¹
Direct	682,778	642,467	657,243	697,326	744,322	1,600,000
Indirect	629,804	794,823	832,426	687,138	875,175	1,600,000
Total	1,312,582	1,437,290	1,489,669	1,384,464	1,619,497	3,200,000

¹ Direct employment for 2002 is based on ITA figures. See text for explanation of the indirect employment number.

Source: EPA, 1995 and ITA.

According to the study, the environmental technologies industries contributed to more than 1.3 million total jobs (direct plus indirect) in the U.S. economy between 1977 and 1991. Out of this total, approximately one-half were estimated to be indirect jobs in upstream industries and jobs resulting from the consumption expenditures of workers in the environmental technologies industries.

³¹ See "Environmental Technologies Industries—Industry Facts." U.S. Department of Commerce, International Trade Administration. Available at web.ita.doc.gov/ete/eteinfo.nsf.

³² See "The U.S. Environmental Protection Industry: The Technical Document." U.S. Environmental Protection Agency, Policy, Planning, and Evaluation. EPA 230-R-95-012. 1995.

Estimated direct employment for 2002 was obtained from the ITA database discussed above. Although the ITA study did not make a distinction between direct and indirect jobs, it is reasonable to assume that the estimated employment number in that study reflected the direct jobs only. Because the more detailed EPA study estimated a multiplier effect approximately equal to 2 for the previous years, the same value was used in Table 3 to calculate the indirect jobs in 2002. Thus, as shown in Table 3, the estimated total employment related to the environmental technologies and their supporting industries in 2002 was approximately 3.2 million jobs. Table 3 also indicates that, between 1991 and 2002, the economy-wide jobs nearly doubled (from 1.6 million to 3.2 million) to sustain the *entire* environmental pollution control technology industries.³³

Employment Growth for FGD and SCR Installations

As discussed above, data on employment levels, particularly for specific components of the pollution control industries, are difficult to estimate. One approach in estimating the overall jobs created by these industries was discussed above. Another approach is to estimate the labor resources required for particular pollution control technologies that have shown significant growth in the period since the CAAA came into effect. This section analyzes the direct labor requirements for installing FGDs and SCRs.

The air pollution control industry utilizes a large number of highly skilled workers, including:

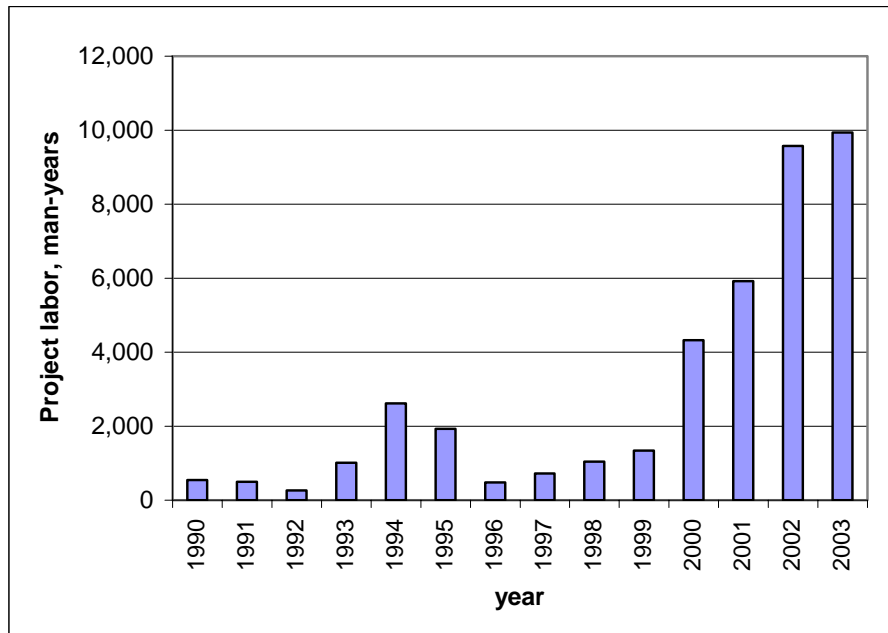
- Engineers;
- Managers;
- Construction trades; and
- Manufacturing labor.

A typical 500 MW FGD system is estimated to require about 380,000 man-hours of engineering, project management, and construction labor. A typical 500 MW SCR system is estimated to require about 365,000 man-hours of labor.³⁴ About 20 percent of this effort are for activities related to engineering and project management, while most of the remainder is related to construction. The direct project labor requirements can be estimated using the data in Figures 2 and 3, and assuming that the projects last an average of 2 years and 2,080 hours per man-year of labor. The results are shown in Figure 11.

³³ The employment estimates presented here cover the whole gamut of environmental technologies, including all media (air, water, and land). In addition to manufacturing jobs, included are consulting and engineering services, as well as jobs in waste water treatment plants. Apart from the *Environmental Business Journal* estimate discussed above, specific and credible estimates for air pollution control equipment only, the focus of this paper, were unavailable.

³⁴ See "Engineering and Economic Factors Affecting the Installation of Control Technologies for Multipollutant Strategies", EPA-600/R-02/073, October 2002.

Figure 11: Estimated Direct Project Labor for U.S. Power Plant SCR and FGD Projects



Thus, SCR and FGD projects alone are estimated to have produced thousands of jobs that would not have existed otherwise. These manpower estimates do not include labor for other air pollution control projects, labor used in the manufacture and fabrication of material and components used in these projects, or home-office employment that is not directly related to specific projects (or the indirect labor requirements, as discussed above). So, the actual employment attributable to the air pollution control market is significantly higher than shown in Figure 11.

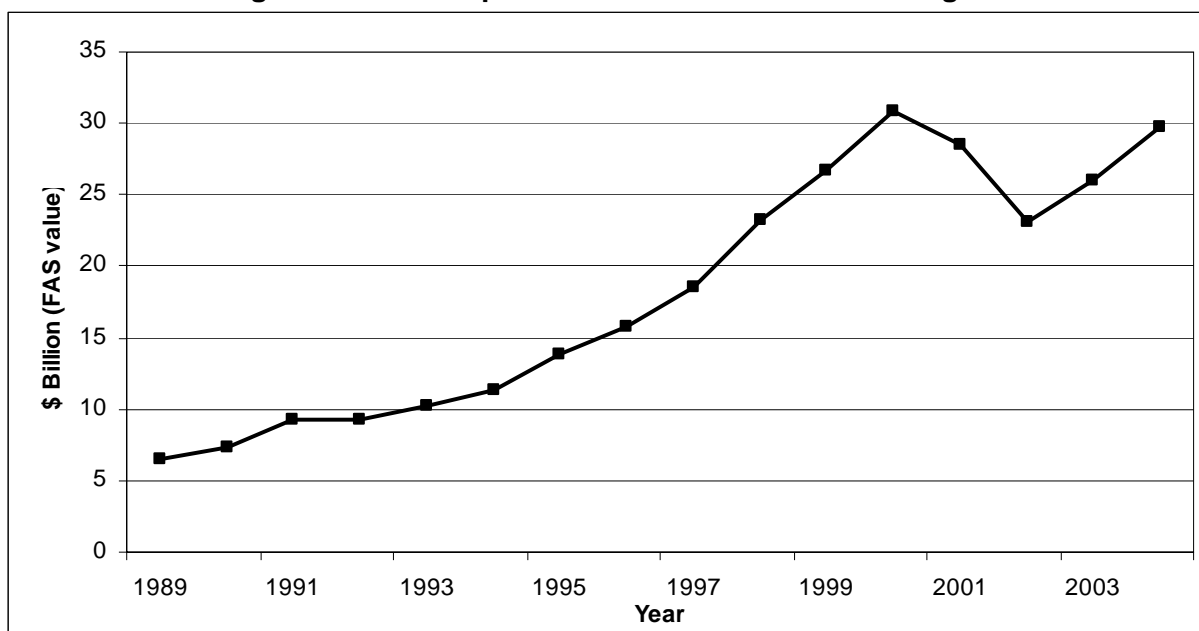
Growth in International Demand for U.S. Pollution Control Technologies

The growth of the U.S. pollution control industry was not confined to the domestic market only. Driven in large part by the air pollution regulations such as the CAAA, the U.S. pollution control industry has been a leader in innovation and technological development, and the results of that leadership have spread beyond the nation's boundaries to other countries throughout the world.

ITA estimated that the global market for environmental technologies in 2002 was about \$556 billion, of which the U.S. market constituted about 38 percent (or about \$215 billion). Note that the ITA definition of the environmental technology industry is much broader than the scope of this work. Not only does the definition include all media (air, water, solid, and toxic waste), it also includes all types of technologies, including pollution avoidance, restoration, and remediation as well as pollution control. Thus, these estimates capture a wider spectrum than is portrayed in the data in the previous Figures.

Out of the \$215 billion U.S. market for environmental technologies, the exports totaled approximately \$23 billion in 2002, supporting some 136,000 to 155,000 *direct* jobs. In the period since the CAAA, the industry grew 37 percent from 1990–2000. U.S. exports of environmental technologies grew at a much faster rate, with growth between 1993 and 2003 being a staggering 130 percent. Although identifying how much of this increase is driven by air pollution control in general, or the CAAA in particular, is beyond the scope of this study, it is perhaps fair to assume that the technologies developed in response to the CAAA have found a market outside the U.S. This spread is perhaps in part because, with the CAAA, the U.S. assumed a leadership role in air pollution control that has been emulated by other countries.

Figure 12: U.S. Exports of Environmental Technologies



Note: F.A.S. Value is the value of exports at the U.S. seaport, airport, or border port of exportation, based on the transaction price, including inland freight, insurance, and other charges incurred in placing the merchandise alongside the carrier at the U.S. port of export.

Source: ITA database.

Figure 12 shows the growth in exports of U.S. pollution control technologies from 1989. U.S. exports peaked in 2000 at approximately \$31 billion, followed by a gradual decline, driven by macroeconomic conditions in the U.S. (industrial downturn), as well as problems in key export markets, such as financial problems in Asia and Latin America. According to the most recent data available, exports have been experiencing a positive growth from 2002 to 2004 (most recent data available). In this time period, exports grew about 29 percent to approximately \$30 billion in 2004.

Table 4 presents total U.S. export of pollution control technologies to the five largest export markets, using 2004 export revenues as the benchmark to determine the rank ordering. Although the growth in exports has been impressive across the board, with Canada showing the lowest growth rate at 15 percent, it has been particularly significant for China and other Asian markets. Export growth to China between 2002 and 2004 was a whopping 125 percent.

Smaller but similar growth patterns also were recorded for other Asian countries, such as Singapore, Korea, Taiwan, and India.

Table 4: U.S. Exports to the Top Five Countries (\$ MM)

	2002	2003	2004
Canada	5,469	6,006	6,269
Mexico	3,596	3,871	4,213
Japan	1,827	1,960	2,252
Germany	1,258	1,428	1,740
China	754	1,152	1,694

Source: ITA database.

As the rapidly growing Asian markets realize the need for sustainable development and look to the advanced countries for innovative pollution control technologies to fuel economic growth, there is significant potential for international growth for the U.S. pollution control industries. Thanks to flexible pollution control regimes, partly due to the CAAA (for air pollution control), U.S. firms can now reap the benefits of innovations and technological developments by expanding their markets in these Asian economies and can lead the way toward a healthier environment worldwide.

Growth in Selected Environmental Technologies

Selective Catalytic Reduction

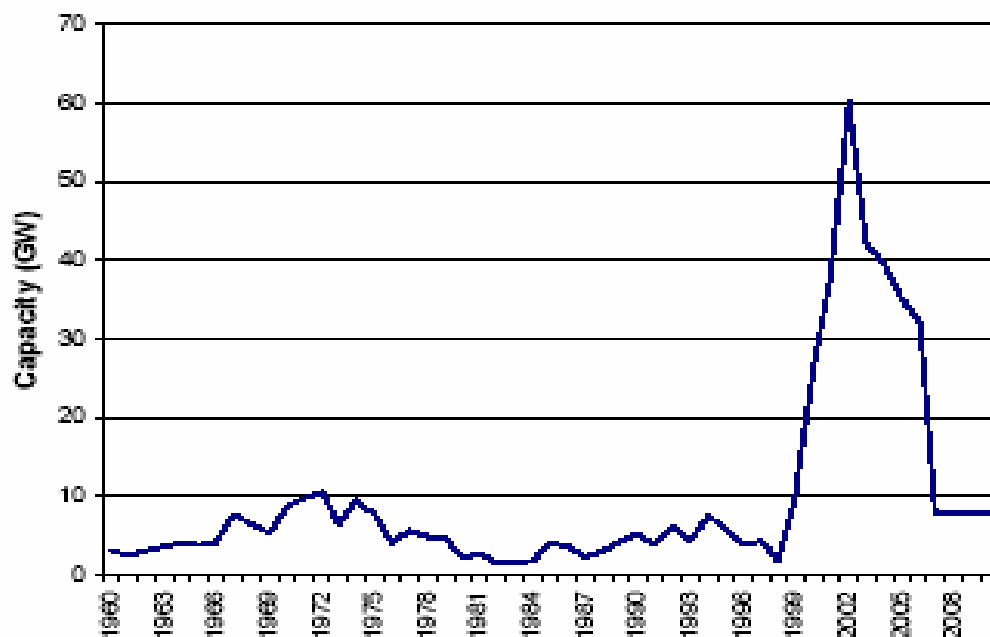
Costs for air pollution controls tend to drop over time. This is because competitive forces exert pressure on technology suppliers to innovate and become more efficient, reducing costs and making their products more attractive to buyers. Moreover, as capability increases, economies of scale lead to cost reductions. SCR catalyst is a good example. When SCR was first introduced to the U.S. market in the early 1990s for coal-fired applications, the cost of catalyst was on the order of \$14,000 per cubic meter of catalyst.³⁵ Since then, about 100,000 MW of coal-fired SCRs have been built along with extensive applications of SCR catalyst in gas turbines. Several new catalyst plants were built in the U.S. to supply the rapidly expanding market, and the economic efficiencies of increased production permitted catalyst suppliers to offer catalyst in the range of \$4,000 to \$5,000 per cubic meter. Even before accounting for inflation, SCR catalyst today costs a fraction of what it did about 10 years ago.

Assuming roughly 1.0 to 1.2 cubic meters of catalyst per MW of coal capacity, the total amount of catalyst sold has been roughly 100,000 to 120,000 cubic meters, for a total revenue of \$400 million to \$600 million for all the catalyst used to initially fill the SCR systems. On average, approximately 15 percent of this initial catalyst is expected to be replaced each year once annual control under CAIR is implemented, resulting in perhaps another \$60–\$90 million in ongoing revenues. Roughly 40 percent of the catalyst in this market is manufactured in the U.S.

In addition to catalyst at coal-fired facilities, it was added at gas-fired facilities. Although the historical average of natural gas capacity addition was in the range of 5 gigawatts (GW) per year, an average of 41 GW per year of gas turbine capacity was brought online between 2000 and 2004, for a total of 205 GW, as shown in Figure 13. Much of that capacity required SCR catalyst to meet NO_x requirements imposed by the CAAA. From Figures 3, 13, and Table 5, it is worth noting that the peak coal-fired SCR start-up date (2003) also coincides with the peak in gas-fired turbine start-up date. As a result, most of the growth in worldwide catalyst manufacturing capacity over the last 10 years was in the U.S. to meet the requirements in these two SCR catalyst markets.

³⁵ See "Status Report on NO_x: Control Technologies and Cost Effectiveness for Utility Boilers," Northeast States for Coordinated Air Use Management (NESCAUM). June 1998.

Figure 13: Natural Gas Power Plants Placed in Service



Source: Institute of Clean Air Companies, "IAQR Projected 2015 Control Technologies can be Installed by 2010", 3/30/04.

Table 5: Coal Boiler SCR Put in Service

Year	SCR Capacity (MW)	# of Units
1995	600	2
1997	200	1
1999	800	2
2000	3,200	5
2001	11,000	17
2002	13,200	23
2003	38,600	71
2004	16,600	46
2005	9,400	19
Total	93,600	186

Source: Institute of Clean Air Companies, "IAQR Projected 2015 Control Technologies Can Be Installed by 2010." 3/30/04.

Continuous Emission Monitoring Systems

Title IV of the CAAA required installation of CEMS on all utility power plants. Furthermore, other provisions of the CAAA have created the demand for CEMS on other pollutant sources. CEMS are integrated sampling, analyzer, and data acquisition systems that extensively utilize advanced technology. CEMS allow an accurate measurement of the pollutants being emitted to the atmosphere. Without these, a reliable indication of the pollution being emitted by sources would be difficult to obtain, as would enforcing emissions control requirements and keeping track of progress in reducing pollutant emissions. Thus, CEMS are a crucial part of any program to control air pollution. Table 6 shows the estimated number of CEMS systems that were installed prior to the CAAA and compares them to the number installed since the CAAA. Total CEMS before the CAAA were estimated to be about 660 systems. Since passage of the CAAA, thousands of CEMS have been installed on existing and new emissions sources, improving the ability to keep track of the pollutant emissions being released to the atmosphere.

Apart from the benefits of improved information on pollutant emissions, CEMS also provide an economic benefit. Most of the CEMS suppliers are U.S. suppliers. According to one such supplier, the impact of the CEMS market has been nearly \$800 million in total system capital cost (this is consistent with the \$600 million total projected by the Institute of Clean Air Companies (ICAC) for 1993–2000). Assuming ongoing support costs are about 15 percent of the capital cost (\$120 million per year), support costs may have accumulated to nearly \$1.5 billion for all systems since original installation -- a large majority of this business going to U.S. suppliers of CEMS sales and service.³⁶

Table 6: CEMS Systems

Period	Number of Systems			
	Full CEMS	NOx CEMS	Appendix E Systems	DAHS
Previous to CAAA (Subpart D CEMS)	400	220		
CAAA, Phase I (Fall 1992)	200			115
CAAA, Phase II (January 1994)	1,050	600	100	680
OTC NOx Budget, NOx SIP Programs	0	450	176	190
New Construction 1992–2004	180	1,425	195	445
FGD/SCR Inlet/Outlet Scrubbers	100	150		
Total Since CAAA	1,530	2,625	471	1,430

Source: Environmental Systems Corporation.

³⁶ Based on data from Steve Drevik, Environmental Systems Corporation (ESC), August 2005.

U.S. suppliers of emissions analyzers are the leaders in this field. According to Jernigan and Dee (2005),³⁷ data for 2003 showed that about 95 percent of the SO₂ analyzers, 97 percent of the NO_x analyzers, 80 percent of the CO₂ analyzers, 60 percent or more of the oxygen analyzers, and 80 percent or more of the flow monitors are from U.S. firms.

CEMS have proven to be reliable as well. According to Jernigan and Dee (2005), EPA reported that the average CEMS data availability is more than 98 percent, and the average relative accuracy of NO_x, SO₂, and flow instruments is 3 percent. These systems thus are providing reliable and accurate information that is important to reducing pollutant emissions.

³⁷J. Ron Jernigan, P.E., DEE, "An Overview of the Current NO_x, O₂, SO₂ Analyzers and Sample Acquisition Technologies and Equipment Installed by the Electric Utility Industry," Second U.S.-China NO_x and SO₂ Control Workshop, August 2–5, 2005, Dalian Bangchui Island Hotel, Zhongshan District, Dalian, Liaoning Province, The People's Republic of China.

VIII. Conclusion

Looking back on the challenges posed by the CAAA, and the responses to those challenges by industry and government, the progress made as a result of emissions control innovations is striking. As detailed in this paper, improvements to control systems have provided greater levels of control, often at *lower* costs. Rates of NO_x and SO₂ removal from power plants have increased continually, at lower capital and operating costs. Dramatic drops in per-mile emissions from gasoline and diesel engines were achieved through the integration of electronic control systems and catalysts without serious consequences for performance or fuel economy. Ozone-depleting substances have been virtually eliminated from industry through product substitution and process changes without the debilitating consequences that had been feared. The prominent examples described in this paper could be multiplied many times in the recent histories of emission controls across stationary, mobile, and area sources. Furthermore, the future promises even more progress, through innovations in multipollutant control systems for power plants, the adaptation of catalysts to diesel engines, and the spread of advanced control systems to smaller and more varied sources, such as industrial boilers and off-road engines.

In reviewing the regulatory context in which this progress took place, it becomes clear that the dramatic improvements in technology did not arise automatically and exogenously. Instead, it appears that the CAAA's key characteristics actively fostered and facilitated these changes. These characteristics can be identified as focusing ultimately on results, a willingness to engage in technology forcing, flexibility in implementation, and a long time horizon. In combination, these characteristics had the effect of organizing an unusually fruitful decades-long process of development, learning, feedback, and refinements in both technology and regulation. Some of the most important elements in this process are touched upon below.

A Focus on Results

Ultimately, the goals of the Clean Air Act and the CAAA are defined in terms of protection of human health and the environment rather than in terms of the installation of particular technologies, reaching specific levels of control, or even the achievement of predefined levels of pollution in ambient air. The broad nature of these goals has made it possible to continue to mandate improvements in controls even as the economy expanded, the problems of ozone transport made regional strategies more vital, and understanding of the dangers of air pollution grew, including fine particulates and longer-term ozone exposure.

Technology-Forcing Regulations

A focus on the need to protect human health and the environment without regard to cost leads inevitably to a willingness to mandate emissions reductions that do not appear possible with existing control systems. Intuitively, it should be clear that inventing and perfecting systems that reduce emissions to an unprecedented degree will require investments in research and development that are unlikely to be undertaken without the motive of requirements or profit. Thus, little can be achieved if regulations are always limited to setting standards that can be reached by applying existing technology. Rather than remaining content with what already exists, the regulatory processes set in motion by the CAAA often leave sources with the responsibility of finding new solutions to the problem of reducing emissions. Time and again, when sources have been given this responsibility, they or their suppliers have come through with innovative solutions.

Flexibility in Implementation

An important complement to the CAAA's emphasis on the importance of its goals is the flexibility it provides in the routes to reaching them. This flexibility is founded on the fact that implementation decisions can take cost effectiveness into account even though the standard-setting process cannot. Perhaps the most prominent example of flexibility is the cap-and-trade system introduced in the Title IV Acid Rain Program. Through that mechanism, the government ensures that it meets its goal of cutting SO₂ emissions from large power plants to 9 million tons per year, while stepping back from any control over which sources make the reductions or what means are used. As a result, there were surprising shifts in the use of low sulfur fuel, surprising increases in the effectiveness of scrubbers, and consequently a surprising drop in the marginal and total costs of the control program.

Many other forms of flexibility can be seen in the operation of the CAAA. The emphasis on performance standards rather than technology standards, the employment of voluntary "opt-in" strategies to find lower cost sources of emissions reductions, and the reliance on state-developed plans for attaining air quality standards, backed by regional control programs and (ultimately) by federally imposed plans, are three other important areas of flexibility. Ultimately, the flexibility allowed by the CAAA gives extremely wide scope to potential innovators, and maximizes the chances that they will be able to find effective and efficient ways to reduce emissions.

Long Time Horizons

The goals of the CAAA were not limited to problems that could be solved immediately. Numerous advantages flowed from the long time horizons built into the amendments, which included multiphase and multitiered programs, as well as the possibility of revised standards and new programs to help meet those standards. First, potential innovators could count on future markets for their new systems, even if the development process took many years. Second, feedback on which regulatory and technological approaches worked best could be applied in the next round of regulations and emissions reductions. Again, the use of market-based systems provides one of the best examples of this phenomenon: The success of the Title IV cap-and-trade program provided EPA with the blueprint for further successes in the NO_x SIP call, CAIR, and the Clean Air Mercury Rule (CAMR). Similarly, the technological advances seen in the Acid Rain Program and the SIP call made tighter caps appear feasible, which in turn helped lead to CAIR. Also, as a general rule, technology improves and becomes less expensive as experience in building and using control devices accumulates, through the process of "learning-by-doing."

Compatibility with Economic Growth

One final lesson from our nation's experience with the CAAA is that, despite the considerable cost of cleaning up the air, it is clearly possible for the economy to thrive along with the environment. Investments in pollution control technologies brought about by the CAAA, among others, not only led to growth and technological innovations for various industrial sectors, it also led to job creation in skilled and semiskilled labor. As shown in this paper, the aggregate economic impacts of these investments went beyond the confines of the pollution control industries by supporting other upstream activities through indirect multiplier effects. Moreover, another benefit from these investments resulted from the increased consumption expenditures of the workers who work in these industries (this effect is also known as induced impacts in regional economics).

Finally, being at the forefront of pollution control in the world has meant that U.S. companies have been one of the leaders in exporting new and innovative technologies to the rest of the world, with significant, but mostly untapped, growth potential in the emerging Asian economies. A track record of innovations in the attempt of U.S. environmental technologies industries to meet the standards set under the CAAA has now put those companies on a path to be a leader in helping developing countries do the same and achieve sustainable development.